TÜRKİYE CUMHURİYETİ'NİN YÜZÜNCÜ YILI

New Perspective in Restorative Dentistry

Editör
Lena BAL

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New Perspective in Restorative Dentistry

Editor: Dr. Öğrt. Üyesi Lena BAL

ISBN: 978-625-372-262-3

Page Layout: Gözde YÜCEL

1st Edition:

Publication Date: 25.06.2024

BIDGE Publications,

Certificate No: 71374

www.bidgeyayinlari.com.tr - bidgeyayinlari@gmail.com

Krc Bilişim Ticaret ve Organizasyon Ltd. Şti.
Güzeltepe Mahallesi Abidin Daver Sokak Sefer Apartmanı No: 7/9 Çankaya / Ankara

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CHAPTER I

Applications of 3D Printing in Restorative Dentistry

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Introduction

In 1986, Charles Hull presented three-dimensional (3D) printing technology, which has since been developed into a diverse range of manufacturing technologies employed in numerous industries, including aerospace, defense, art, design, architecture,

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engineering, medicine, and dentistry. It allows individuals to personalize designs and fabricate unique objects (Barazanchi et al., 2017).

Three-dimensional printing, as a broad term for a manufacturing process, refers to the building of an object layer by layer, adding layers until the product is formed. The term 'additive manufacturing', 'rapid prototyping' or ‘generative process’ is a precise description of 3D printing. Three-dimensional printing is emerging as a promising technology in a wide variety of fields, there has been a significant expansion in the use of three-dimensional (3D) printing in the medical and dental professions, facilitated by advancements in Computer Assisted Design (CAD) and Computer-Aided Manufacturing (CAM) technologies (Dawood et al., 2015a). If utilized correctly, 3D printing has the potential to enhance patient care and the role of radiologists in that care.

Medication can be customized based on the anatomical information that radiologists regularly gather and analyze and delivered via 3D printing (Ballard et al., 2018). In the medical industry, 3D printing has proven to be a valuable tool in the production of more lifelike models for treatment and surgical planning, as well as for training, research, and instructional purposes. It has been applied to a number of dental treatment techniques. This article reviews the most recent developments in 3D printing applications for restorative dentistry.

Three-Dimensional printing techniques

In the medical and dentistry, volumetric data can be accessed with relative ease through intra-oral or laboratory optical surface scan data, as well as CT and CBCT data. Advancements in computer technology and software have benefited 3D printing greatly (Dawood et al., 2015a).

The creation of a virtual model of the object to be built represents the first step in the 3D printing process, which then turns the data into a digital file. The printer can then follow the virtual design created by a 3D modelling tool. The utilization of computer-aided design (CAD) software is essential for the generation of new objects from scratch (Jawahar et al., n.d.-a). Three types of 3D printing processes can be distinguished on the basis of their different operating principles: Powder Bed Fusion (PBF), light curing and Fused Deposition Modeling (FDM).

1. Powder bed fusion (PBF)

Laser sintering or fusion technologies could be applied to any powdered material that can be sintered or fused by laser radiation and solidified by cooling (Mazzoli, 2013). PBF is divided into the following printing technologies: selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM) and direct metal laser sintering (DMLS).

These categories are based on the energy sources and powder ingredients (Galante et al., 2019). In all of these processes, the powdered materials are subjected to the application of heat in order to facilitate their melting. A number of metal products are manufactured in dentistry using PBF, including dental implants and dental implant supported prostheses (Revilla-León et al., 2020). Additionally, PBF exhibits a great deal of promise in the production of ceramic restorations (Methani, Revilla-León, et al., 2020), which can be applied to the production of models, frame crowns, and model casting abutments. PBF provides users with a substantial degree of design flexibility, offering a wide range of applicable technologies and materials (Methani, Revilla-León, et al., 2020).

1.1 Selective laser sintering

The fundamental principle underlying this technique is the use of lasers (e.g. Nd-YAG) to sinter or bond powdered material layer by layer, thereby forming a solid structure. The process is applicable to a wide range of thermoplastic materials, polymers, metals and ceramics.

Due to the high melting points and low plasticity of ceramics, they are more difficult to produce with SLS than other materials. Ceramic production with SLS is divided into two: direct and indirect techniques. In the direct technique, ceramic particles are combined to obtain the sintered object, while in the indirect technique, the fusion of ceramic particles is based on the polymeric binder phase. The green bodies created then go through 2 heat processes. These are debonding and sintering (Methani, Cesar, et al., 2020).

1.2 Selective laser melting (SLM)

In this production technique, the metal powder is completely melted. Consequently, a greater input of energy is required in this technique. The complete melting of the material ensures that the formation of porous internal structures and surfaces is prevented (Galante et al., 2019). This method allows the production of materials with superior mechanical properties and higher densities. The most common laser used in SLE to process metal powder is the CO2 laser. The disadvantage of this production technique is that there are temperature fluctuations during production. This situation occurs due to high internal tension in the material to be produced.

Subsequently, the processed materials must undergo heat treatment (Sciences et al., 2021).

1.3 Electron beam melting (EBM)

The EBM technique uses an electron beam to melt the material (Tian et al., 2021a). This technique exhibits a lower residual stress than other powder bed methods, resulting in a reduced distortion of the produced object. The energy consumption is lower than that of SLS, and the production of layers is faster. This method is most useful in industries where high-value products are manufactured, such as aerospace, defense, motorsport and medical prosthetics (Methani, Revilla-León, et al., 2020). The raw material (either metal powder or wire) is placed in a vacuum and subjected to heating by an electron beam, which is used to melt and fuse the material together. The advantages of this system include the ability to achieve high energy levels with fine beam beams, the capacity to remove impurities in a vacuum, low energy consumption, and a minimal requirement for maintenance. The system's disadvantages include the necessity for expensive vacuum maintenance, the production of X-rays during the manufacturing process, and the requirement for frequent maintenance (Javaid & Haleem, 2019).

1.4 Direct metal laser sintering (DMLS)

In this technique, laser beams are used to melt metal powder and metals are produced layer by layer (Diş et al., 2024). SLS and Direct Metal Laser Sintering (DMLS) enable production in the same way and are often used synonymously. However, the difference is that SLS is used to refer to the process applied to various materials (plastics, glasses, ceramics), while DMLS refers to the process applied to metal alloys (Javaid & Haleem, 2019). It should be noted that depending on the material, dimensional distortion due to porosity and shrinkage may be observed (Tian et al., 2021a)

2. Light curing

A class of 3D printing techniques known as "light curing technology" employs photosensitive resin ingredients that are cured and shaped by light irradiation. The technology is comprised of three primary techniques: stereolithography (SLA), digital light processing (DLP) and photo jet (PJ).

2.1 Stereolithography (SLA)

The components of SLA, one of the first widely used 3D printing technologies, include an ultraviolet (UV) laser to cure the resin, a platform for building models, and a reservoir for the photosensitive liquid resin material source. During the building process, the build platform is immersed in liquid resin, and a UV laser is used to polymerize the resin. Subsequently, the build platform is advanced by a distance equal to the thickness of a single layer, with the previously applied layer being covered by the uncured resin (Barazanchi et al., 2017; Methani, Revilla-León, et al., 2020).

In SLA technology, there are two methods for moving the platform. The platform's top-down movement is the first. The building platform that has been submerged in the resin reservoir is covered in a layer of resin. A wheel next to the construction platform adds a fresh layer of resin as it descends after the laser has scanned the first layer. Until the item is produced, the build cycle is repeated. In contrast, only one layer of resin can spread across the space between the platform and bottom in the platform-bottom-up method because the platform is submerged at the bottom of the resin reservoir. The resin layer would be scanned with the laser positioned at the reservoir's bottom. The platform spreads out one layer after curing, and gravity allows the resin material to fill in the space between the platform and the bottom. Compared to the platform-top-down strategy, the platform-bottom-up approach has a few advantages. First, the platform-bottom-up strategy uses light curing at the bottom to prevent oxygen interference, whereas the second way places the resin in direct contact with oxygen throughout the polymerization process. Second, there is less chance of harm to the operators because the laser is positioned at the bottom. Third, gravity allows for the automatic refilling of the resin. As a result, this technology is now introduced by the majority of SLA printers (Kessler et al., 2020).

A variety of ceramic and photopolymer resin materials with distinct colours and physical properties have been developed for use in this method. The resins include hard resin, low-residue resin (for precision casting), clear resin, and flexible polyurethane resin (Javaid & Haleem, 2019).

In the field of ceramics, SLA employs a selective curing process whereby ceramic particles are incorporated into a curing resin. The ratio of ceramic powder content to resin must be adjusted since the mechanical properties of the structure are influenced by the viscosity of the slurry. Polycrystalline ceramic crowns can benefit from the good mechanical resilience of ceramics with varying chemical compositions, including zirconia and alumina (Dawood et al., 2015a). Consequently, SLA's research and development efforts are focused on this specific type of ceramic.

2.2 Digital light processing (DLP)

The DLP technology microsystem is composed of a digital microreflector device, which is a rectangular configuration of mirrors. The number of mirrors determines the resolution of the projected image, with each mirror denoting a single pixel. The angle of each microreflector can be altered independently. The micromirror reflects the light emitted by the light source, which is subsequently projected as a single pixel onto the surface to be printing (Barazanchi et al., 2017; Methani, Revilla-León, et al., 2020). One advantage of DLP technology is that a full layer can be created by a single laser irradiation, in contrast to SLA technology, which employs a sequential laser scanning of the layer. The construction time can be reduced since each layer is constructed independently of the other layers' shapes or pixel counts (Tian et al., 2021b).

2.3 Photo jet (PJ)

The principle of PJ is a photopolymerizable inkjet, in contrast to the two patterns mentioned above, which polymerize liquid monomers and oligomers at specified spots. A UV lamp emits light in the direction of the printhead's movement to cure the photopolymer on the building surface and finish the first layer of printing. The printhead moves along the X/Y axis as the photopolymer is sprayed onto the table. The device then repeats the build cycle until the object is printing, lowering the table by one layer along the Z-axis. This method is unique in that it works with a wide range of materials, including zirconia paste, thermoplastics, resins, and ceramics.

One special benefit is that all the materials on the list can be printing and fused. This method is distinctive in that it can work with a diverse range of materials, including zirconia paste, thermoplastics, resins, and ceramics. The capacity to print and fuse any of the materials on the list confers a distinct advantage upon this technology in comparison to competing technologies. Furthermore, the ability to print multiple materials in a single location enables the blending of elements to create objects with a range of characteristics. This contrasts with other 3D printing technologies, which are unable to print multiple materials in the same location (Arnesano et al., 2020). Photopolymer injection technology enables the production of items with exceptionally high surface quality and print resolution, obviating the necessity for surface polishing with thin layers (Tian et al., 2021b).

3. Fused deposition modeling (FDM)

One of the most widely used and cost-effective 3D printing methods in dentistry is FDM (Arnesano et al., 2020). The nozzle heats and melts the filamentous thermoplastic substance. The molten material is extruded and ultimately solidified by building up layers of material to produce the product, with the computer controlling the movement of the nozzle and worktable in the X- and Y-axes, respectively (Barazanchi et al., 2017; Dawood et al., 2015a).

Among the engineering thermoplastics frequently utilized for FDM applications are polylactic acid (PLA), polycarbonate, polyamide, and acrylonitrile-butadiene-styrene copolymers (Ligon et al., 2017). PLA is a more environmentally friendly option and is suitable for use in the mouth. Medical-grade polycarpic acid-tensioned tricalcium phosphate scaffolds produced using FDM have been demonstrated by Yefang et al. to be biocompatible, possess good mechanical strength, and can be utilized as tissue scaffolds in dentistry (Yefang et al., 2007). Furthermore, Chen et al. demonstrated that plaster models may be fitted with custom pallets manufactured using FDM technology (Chen et al., 2016).

The variables that affect the products of 3D printing

Printing products are impacted by several variables, including material composition, postprocessing, printer process parameters, and ultimate tensile stress, yield strength, impact strength, and induced residual stress. These variables primarily show up in the form of accuracy, processing time, and material properties.

Biomaterials for 3D printing in dentistry

1. Polymers

Plastics, composites, metals, ceramics, and biomaterials are among the materials that may be used for 3D printing. The most widely used 3D-printing polymers include polycarbonates, poly (lactic acid) (PLA), polyetherimide, and acrylonitrile butadiene styrene (ABS) (Dong et al., 2018).

1.1 Polycaprolactone (PCL)

PCL is a semi-crystalline thermoplastic resin, with a crystallinity level of around 45%. Medium-density polyolefins and PCL share comparable mechanical characteristics. PCL has a waxy feel and a comparable appearance to medium-density polyethylene's milky white color. The melting point and decomposition temperatures of PCL are around 63 °C, 60 °C, and 250 °C, respectively (Rosales-Ibáñez et al., 2021).

There is limited use for PCL because of its low melting point—it softens at roughly 40 °C. This excellent biodegradable polymer will break down gradually in soil over an average of 12 to 18 months. Additionally, PCL is an aliphatic polyester with weak osteoconductivity and high mechanical qualities as well as a lengthy resorption period (Lin et al., 2019a). It has become essential to debase it using hydroxyapatite and other biomaterials to improve its self-biocompatibility. Furthermore, more research is required to ascertain the ideal proportion between the two in terms of biocompatibility.

In a previous study, the whole scaffold surface was shown covered with human fibroblast cells in microscope images. The proliferation and survival of fibroblasts in the culture was confirmed by immunofluorescence. It may be inferred from the in vitro culture data that PCL has high biocompatibility(Lin et al., 2019a). According to different research, the micrographic PCL improved in vivo tissue organization (bone-ligament constructions). The creation of bone-ligament constructions for dentistry and orthopedic therapeutic settings may benefit greatly from this finding in terms of clinical applicability (Pilipchuk et al., 2016).

1.2 Polylactic acid (PLA)

PLA is a biocompatible, water-insoluble polymer that is employed in the biomedical industries (Tagami et al., 2018). PLA is thought by researchers to be a stiff polymer matrix (Evans et al., 2018). With a 12% elongation at break, 59.7 MPa tensile strength, and 50.7 MPa flexural strength, PLA possesses the mechanical properties of a pure 3D material under ideal conditions(Liu et al., 2018). Polyester derived from renewable monomers is called PLA (Luzuriaga et al., 2018).

Due to its biocompatible and biodegradable qualities, simplicity of processing, thermal stability, and ease of processing, PLA has drawn interest from the scientific community (Lin et al., 2019a). The research confirmed that cell-derived decellularized matrices could be prepared on 3D-printing scaffolds for manufacture as ideal-shaped 3D scaffolds. This research verified that decellularized matrices obtained from cells may be created on 3D-printing scaffolds to create precisely shaped scaffolds. Therefore, several experimental tests are required to guarantee the correctness of the experimental data (Lin et al., 2019b). One of the most promising options to address the current energy and environmental issues is PLA. A practical and environmentally friendly platform for PLA applications in bone tissue creation is provided by the programmable 3D building approach (Tagami et al., 2018).

1.3 Acrylonitrile butadiene styrene (ABS)

The suggested printing temperatures for ABS, an oil-based, lightweight, and durable polymer (Derkach et al., 2020). The researchers verified that in the tensile test, the ultimate strength was 224 MPa, with Young's modulus of 0° printing direction up to 1.81 GPa (Khatri et al., 2018; Zhang et al., 2018). According to the results of the creep test, the plastic creep model 90° in the printing direction had the lowest creep resistance, which is 0.2°. 3796 cycles were performed on average under a 30 N load during the fatigue test.

Based on everything shows above, ABS performs well overall, and has a strong impact resistance (Zhang et al., 2018). To examine the effects of printing direction, density, printing time, and filler form on the stiffness, strength, and failure processes of 3D-printing ABS structures, tests under compressive loads were conducted. An examination of the stress-strain (σ–e) curves reveals that increasing the filling content raises stiffness and limited strength correspondingly (Lin et al., 2019a).

1.4 Poly lactic-co-glycolic acid (PLGA)

PCL and PLGA are thermoplastic materials that may be 3D printing using the fused deposition modeling approach to create scaffolds with controlled morphology, high porosity, and mechanical strength (Larsson et al., 2016). Owing to its biodegradability and biocompatibility, polylactic acid (PLA) and polyglycolic acid (PGA) copolymer, or PLGA, has found widespread application in a variety of Food and Drug Administration (FDA) approved therapeutic devices, including grafts, sutures, and macro/micro/nanoparticles (Zehnder et al., 2016). It stands out in the biomedical area because of these exceptional qualities and effective performance when compared to other materials (Yahata et al., 2017).

Different PLGA varieties can be produced with varying monomer ratios. For example, PLGA 75:25 indicates that 75% of the polymer is made up of lactic acid and 25% is made up of glycolic acid. The glass transition temperature of 40–60°C is shared by all PLGAs, which are all amorphous. It may dissolve in several solvents, such as acetone, ethyl acetate, tetrahydrofuran, and chlorinated solvents (Lin et al., 2019a). It's interesting to note that the breakdown rate accelerates and takes approximately two months when the ratio of the two monomers is 50:50. Lactic acid and glycolic acid, byproducts of human metabolic processes, are the breakdown products of polylactic acid. Except in cases of lactose deficiency, they do not exhibit harmful side effects when employed in biological materials and medications. PLGAs are extremely thermolabile compounds (Kumar et al., 2017). Because PLGA has a well-established track record of safety in clinical settings, it has been chosen as an appropriate material for the creation of biodegradable microspheres (Ji & Guvendiren, 2017). From a biomedical perspective, PLGA has a wide range of application opportunities and merits more investigation and advancement (Lin et al., 2019c).

2. Bio- inorganic materials

Inorganic biomaterials are used extensively in 3D-printing. Nevertheless, the materials used in dentistry that are 3D-printing are still in the early stages of development. They have fewer therapeutic uses than organic polymer molecules, and dentistry practitioners seldom employ them for medical interventions (Lin et al., 2019a).

2.1 Ceramic

Ceramics, particularly zirconia ceramics, have been extensively advocated for use in dentistry as restorative materials because of their flawless aesthetic qualities. Zirconia dental restorations in digital dentistry are mostly produced using digital manufacturing methods (such as CAD/CAM or 3DP) (Lin et al., 2019a). The sintering procedure is necessary to improve the mechanical qualities after production.

Zirconia repair has a low accuracy rate. As a result, teeth that have been restored with poor adaptation are susceptible to microleakage or secondary caries. The goal of 3D printing is to replace the expensive CAD/CAM processing with a manufacturing technology that produces extremely precise objects after sintering. Nevertheless, it is impossible to forecast and conduct a comprehensive study of the 3D-printing product's shrinkage. Dental crowns made of porcelain fused to metal (PFM) are a popular option for dental restorations because of their great compressibility, tensile strength, and white, tooth-like look because of their great compressibility, tensile strength, and white, tooth-like look (Lin et al., 2019a).

2.2 Hydroxyapatite (HA)

Since HA makes up the majority of bones, it has several exceptional benefits, such as the ability to be used as a prefabricated material for hard tissue bioprinting. It offers a wealth of resources and may be synthesized or manufactured from hard structures and sintering procedures. There are natural HA particles with excellent osteoconductivity and high biocompatibility. HA may be used in 3D printing technology in a variety of forms, including granules, slurries, and powders. Normal methods for acquiring the fluidity needed for the 3D printing process include granulating or combining with different polymer solutions (Lin et al., 2019a). Kaiser initially suggested apexification in 1960. To promote apical closure, most academics employed calcium hydroxide preparations, with varying degrees of success (Qin et al., 2018).

Reports on the application of pastes made of hydroxyapatite are few. It has been proposed that a somewhat low paste fluidity leads to an inadequate root canal filling particularly in the molar narrow, and ultimately the failure of the therapy. Glycerin is used to prepare it, and then iodoform that has been dissolved in glycerin is added to create a soft, paste-like consistency.

It has a particular viscosity, excellent adherence, antibacterial action, x-ray blocking, and convenience for clinical evaluation. It is also simple to fill (Lin et al., 2019a). Interestingly, despite the use of medicines to cause the apical development of the root, some research does not recommend overfilling young permanent teeth. It has been proposed that an underfill of up to 2-3 mm is beneficial for the development of the apical area. It could have to do with HA's exceptional biocompatibility, which inhibits the stimulation of both hard and soft tissues. Although HA is not osteogenic in and of itself, it can offer a physiological matrix that is conducive to the formation of new bone, promoting the regrowth of surrounding tissue and the cementum deposition that closes apical foramina (Lin et al., 2019a).

Controlling the infection in the root canal is essential for the successful completion of an apical-inducing angioplasty. HA paste is a clinically defensible substance for apical induction (Lin et al., 2019a).

2.3 Zirconia

Conventional cast metal studs are made from alloys such as Cr, Ni, or Co-Cr. On the other hand, some persons are allergic to chromium and nickel. Due to the ion exchange properties of these metals, prolonging the procedure may cause patients' eyelid edges to become discolored, which might affect how they look. Metal posts and cores may pass through the crown's rim and outer edge if all ceramic crowns are restored. This might have an impact on the restoration and aesthetic procedure.

Zirconia was initially used on the completed post and core system due to its better mechanical properties. Moreover, zirconia is safe for people and does not cause toxicity or allergies due to its high biocompatibility. To summarize, zirconia ceramics offer a great deal of potential applications since they are ceramic materials with high strength and hardness. The fast advancement of nanotechnology has led to a greater focus on nanoscale zirconia (Lin et al., 2019a).

2.4 Plaster

Calcium sulfate makes up the majority of this cementitious substance that air-hardens, called plaster. Plaster-based cementitious materials and related products are widely utilized in dental tissue engineering because they have many great properties, are abundant sources of raw materials, and need little energy to produce. Gypsum's little expansion gives its products a delicate texture, white appearance, smooth surface, and exceptional processability, which makes it a great material for sculpting (Lin et al., 2019a).

In a study, that a stereolithographic 3D printer (SLA) with a horseshoe-shaped design prints the digital models, and the Pearson correlation coefficient was used to assess each model type's measurement reliability. Despite the transverse measurements, the measurements on plaster models and printing models have revealed some significant discrepancies in tooth dimensions and intrusive characteristics; nonetheless, these changes are not medically important. On the printing models, the upper and lower intermolar distances are statistically significant and have medical implications (Camardella et al., 2017).

3. Metal

Metal substance used to fix orthodontic teeth and tooth deformities is dental metal. These metal materials need to be non-toxic, innocuous, resistant to tarnish and corrosion, possess a specific amount of strength and durability, be able to conform to the hard and soft tissues in the mouth cavity and be simple to work. Metals and their alloys may be used to create filler materials for 3D-printing crowns, bridges, dentures, and other dental materials. They also offer perfect properties that are necessary for dental metal materials (Lin et al., 2019a). Co-Cr alloy is lightweight, strong, and has good resistance to corrosion and wear (Lin et al., 2019a). Titanium alloy is very lightweight and resistant to corrosion. It is less expensive than precious metals and has better compatibility with the human body than other alloys. Crowns, bridges, and several types of dental implants (chin and dental) can be made using it. When it comes to creating orthotic appliances, Ti-Zr alloy outperforms stainless steel because of its higher toughness. It is a high-performing wire material used in dental orthodontics (Kim et al., 2018).

3.1 Cobalt-chromium alloy (Co– Cr)

Cobalt-chromium (Co-Cr) alloys have become more popular in the field of crowns and fixed dental prostheses because of their perfect mechanical properties and reduced cost compared to high-noble alloys (Daou et al., n.d.). On the other hand, several of the issues surrounding casting in the traditional production process are well documented. With Co-Cr alloy, casting shrinkage has essentially been eliminated; nevertheless, the accuracy can be impacted. In addition, the alloy's high hardness index increases the difficulty of finishing. A recent advancement in CAD-CAM use offers improved standardization (SorrenTino et al., 2017).

The standard technical examination conducted by the United States Public Health Service (USPHS) revealed the exceptional clinical performance of Co-Cr SC. No follow-up evaluation revealed any significant variations in the mean periodontal parameters between the test and control teeth. In conclusion, CAD/CAM Co-Cr single crown is a successful treatment choice for the posterior area following 4 years of clinical functional verification (Lin et al., 2019a).

3.2 Titanium- containing materials

The enhanced fatigue resistance of commercially pure titanium dental implants has been linked to their greater strength, which may outweigh that of the stronger Ti6Al4 alloy, in the broader area of biomedical devices and implants. With such a property, those materials would be powerful substitutes for the titanium alloy that is now in use as well as biocompatible (Oweis et al., 2017).

The goal of much recent research has been to increase titanium surfaces' medicinal effectiveness (Li et al., 2018). Titanium (Ti) is a biomedical material that is commonly used in plastic surgery and dentistry because of its exceptional mechanical qualities, low density, great corrosion resistance, and good biocompatibility. One area of ongoing study is the tribological corrosion behavior of titanium alloys. The integration of titanium dioxide (TiO_2) into biomaterials presents a great technological opportunity because of its antibacterial and photocatalytic properties (Pantaroto et al., 2018).

Applications of 3D printing in restorative dentistry

Since technology has improved over time, 3D printers have generally provided a wide range of treatment options. These options include lower production costs and times, a clean, safe, and quick production process, digital storability, and the capacity to produce complex cases with few errors (Tamimi & Hirayama, 2019).

Three-dimensional printing can be done using a variety of methods; the ones most frequently used in restorative dentistry are material extrusion, powder bed fusion, directed energy deposition, material jetting, and photopolymerization. 3D printers generally used in dentistry; It can print metals such as resins, tires (PLA -TPA), glass, ceramics, zirconium and titanium. The first 3D printers were generally produced using the "Fused Deposition Modeling (FDM)" method. However, this method is not used today due to unclear details, porosity, and the physical strength of the material not being suitable for intraoral conditions (Peşkersoy, 2022).

The majority of dental methods are based on a mix of concepts. For instance, the process of Selective Laser Sintering/Melting (SLS/M) uses a laser as a directed energy source, and powder bed fusion—where powder is deposited on a build platform—is used to fuse particles together. The surplus powder is easily removed from the layer using a roller once the metal particles have sintered together. Subsequently, another layer of powder is deposited on top of the previously produced layer as the build platform drops to a height equal to the thickness of the newly formed layer. The majority of technologies employ a build platform where a single layer of material is placed, processed, and cured before being added to in layers to create a three-dimensional item (Beleges et al., 2021).

Since aesthetics are as important as function and hygiene in restorative dentistry, Digital Light Projection (DLP) and Stereolithography (SLA) printers have been developed instead of these 3D printers, which can produce epoxy resin-based composite / ceramic hybrid materials and polymerize them with heat and light.

The key factor in both methods is that layers of parts are prepared one by one from a photo-polymer resin, attached to each other using an ultraviolet laser, and polymerized with ultraviolet light to form the entire restoration. While the main advantages of SLA are the rapid and low-cost production of large amounts of restorations or models, the most important development in DLP is that the details are created more clearly, and the material used is optimized for intraoral conditions. 3D printers used for restorative dentistry Although of different types and features, generally FDM printers and whitening plates, dental retractors and isolation sets; Inlay, onlay, veneer restorations and temporary and permanent single crowns can be produced with DLP printers (Peşkersoy, 2022).

Dentistry is using additive manufacturing (AM) techniques more and more. To construct a computer-aided design (CAD) item, a range of AM techniques and materials can be utilized. The combining of material layer by layer using 3D data models is the fundamental technique of additive manufacturing. The foundation of all additive manufacturing methods is a two-tiered process chain for creating three-dimensional physical components: the virtual level comprises data collection and processing, while the actual level involves further postprocessing (Jockusch & Özcan, 2020). Comparing additive manufacturing to the existing subtractive/milling procedures, there are several benefits. It makes it simple to produce intricate shapes, minimizes material waste that is often wasted during milling, enables precise detail creation, and eliminates issues like microcrack propagation brought on by the pressures used when milling restorative materials. Though the method is becoming more and more well-liked, there hasn't been much research done on it or its use in restorative dentistry (Beleges et al., 2021).

Just 120 μm in dimensional accuracy can determine whether a restorative procedure is physiologically feasible or not. It is crucial to remember that printer quality matters when trying to produce a product on a scale so small that these changes are invisible to the untrained eye. Not all 3D printers are made equal, according to research done on the dimensional correctness of dental casting patterns produced by four distinct kinds of printers (Anadioti et al., 2018; Ishida & Miyasaka, 2016).

It is not unexpected that UV or visible light-based techniques to 3DP are among the first to be applied as dentistry takes use of this rapidly growing technology, as photopolymerization has historically been widely utilized in dentistry. Thus, resin is now a popular 3D printing material in dentistry. It is necessary to assess the advantages and disadvantages of 3D printing resins as they relate to the area of dentistry because they are known to produce some shrinkage because of mechanical and light-activated polymerization capabilities (Jawahar et al., n.d.-b).

1.Tooth models

When used in conjunction with an intraoral scanner, dental dies may be 3D printing without the requirement for a plaster model. Traditionally, wax patterns and copings for intracoronal and extracoronal restorations are made using plaster models, which are regarded as the gold standard (Beleges et al., 2021). Plaster models cannot copy internal anatomical structures and cannot be accurately reproduced and produced. 3D models can accurately show the details of anatomical structures and can be reproduced with the same accuracy. In this way, they are free from the limitations of plaster models. The data required to produce a 3D model can be archived digitally and physical storage space is not required as with plaster models. Additionally, data can be modified electronically (Dawood et al., 2015b).

2.Wax patterns

Wax model production is the first step in the prosthesis manufacturing process. Rapid prototyping technologies have made it possible to create wax models for different prosthetic applications in layers (Katreva et al., 2016). This process includes the following three steps. First, digitization of the models with a laboratory scanner. Secondly, designing the wax model with software and producing the wax model with 3D printing methods (Revilla-León & Özcan, 2019).

3.Inlays and onlays

Research revealed that while the wax designs were not always better than those created by hand or by milling, they were often sufficient for clinical usage. Resins have been used to print inlays and onlays, and fast prototyping has been used to create wax patterns for ceramic inlays. These have been compared in accuracy to milled restorations and traditional methods. According to studies, milling or traditional methods produce better results than 3D printing for wax designs (Beleges et al., 2021).

4.Single tooth crowns

Single-tooth restorations have been fabricated with additive manufacturing using DLP, SLS, and inkjet printing methods. Metals, ceramics, and hybrid resins are some of the materials utilized in printing. Although not as widely as metal restorations, tooth-colored single tooth restorations have also been created by additive manufacturing using photopolymerized polymers. Research has assessed how the construction layers impact the mechanical characteristics and dimensional accuracy of the resin restorations. In comparison to horizontal layers, it was found that layers constructed vertically, or perpendicular to the direction of load, could endure larger compressive forces. The construction angle affected the crown's dimensional precision (Beleges et al., 2021). Although resins are a popular material for 3D printing, their mechanical and light-activated polymerization qualities have caused significant shrinkage. Therefore, further testing is necessary for 3D printing resins (Jawahar et al., n.d.-b).

Conclusions

The emergence and advancement of 3D-printing technology have opened new avenues for precisely creating complex geometric structures one-of-a-kind using digital data and a range of very complicated and tunable materials. A dentist may create personalized designs for a range of product categories with dental 3D-printing. During this procedure, it is important to consider factors like printer accuracy, software usefulness, printing materials, clinical time savings, improved safety, clinical outcomes evaluation, tooth prototyping, and instructional modeling. Dental crowns, bridges, and other orthodontic device types are among the many items that are produced to treat oral diseases. Further uses of 3D-printing in dentistry will need to overcome several obstacles. Although 3D-printing is a new approach to personalized items and specialized applications, its high cost and relatively poor pace mean that it needs more improvement before it can compete with traditional methods in mass manufacturing of everyday goods.

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CHAPTER II

Composite Materials in Restorative Dental Treatments

Oyun Erdene BATGEREL[1]

Introduction

Composite resins have been widely utilized in restorative dentistry since the early 1960s to recover lost tooth structure due to decay, trauma, or abrasive processes and to create an aesthetic appearance (Moda et al., 2018; Somacal et al., 2020). Unlike amalgam restorations, composite resins offer the significant advantage of preserving healthy tooth structure without the need for removing sound tooth tissue for restoration adhesion, which is one of their most important benefits aside from their aesthetic appeal (Haugen et al., 2020). The 2 mm incremental layering technique for composite resins is considered the gold standard (Ilie & Stark, 2014). However, ensuring that these layers do not exceed 2 mm and

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individually curing each layer with light is time-consuming. Moreover, this technique carries the risk of creating voids between layers and moisture contamination during application (Abed et al., 2015).

To overcome the risks associated with the layering technique, bulk-fill composites developed by various manufacturers have been reported to be applicable in 4 mm increments and curable with light, thanks to their low polymerization shrinkage and high degree of conversion. It has been argued that applying these materials in 4 mm increments can shorten the treatment time and prevent the formation of voids between composite layers (Erdemir et al., 2018).

In contemporary dental practice, the widespread use of composite resins, particularly in the posterior region, necessitates their durability against the challenging conditions of the oral environment over the long term (Valinoti et al., 2008). The increase in consumption of acidic foods and the impact of brushing habits can, over time, lead to surface degradation, altering the surface roughness (Vilela et al., 2021) and microhardness of the restoration (Gehlot et al., 2022). These rough surfaces may facilitate biofilm adherence on the restorations, thereby increasing the risk of secondary caries and periodontal diseases (Vilela et al., 2021). Additionally, surface roughness affects the color, brightness, and stain susceptibility of composite resins (Abuelenain et al., 2015). Alongside surface roughness, the surface hardness of restorative materials is one of the key physical properties affecting the durability of composite resins (Al-Samadani, 2016). Therefore, the ability of composite resins to resist the adverse effects they encounter in the oral environment successfully is feasible with high hardness values (Okada et al., 2001). Consequently, an increase in surface roughness and a decrease in microhardness are among the critical factors affecting the longevity of composite restorations in the oral cavity, leading to the need for their replacement. Hence, especially for composites used in the posterior region, both traditional and current bulk fill composites, the question arises as to how the effects of acidic fluids in the oral environment and brushing will affect their surface roughness and hardness values (Tanthanuch et al., 2021).

History of Composite Resins

The term "composite" is defined as a three-dimensional compound consisting of at least two distinct chemical components with a discernible interface (Yap et al., 2001; Zhou et al., 2019). Composite materials exhibit the properties of each phase they contain and, thanks to the complementarity of the phases, they achieve advanced material properties (Çelik, 2017; Yap et al., 2001).

The first tooth-colored composite material introduced to the market in the 1870s was silicate cement. However, this material was quite brittle and only lasted in the mouth for a few years, requiring mechanical retention (Puckett et al., 2007).

The first polymer-based tooth-colored composite used in dentistry was developed in the 1940s and was based on poly(methyl methacrylate). Initially, despite being aesthetically pleasing, these materials exhibited various problems, including poor color stability, high thermal expansion coefficient, lack of bonding to tooth structure, and high polymerization shrinkage.

One approach to addressing the issue of polymerization shrinkage involves the use of high molecular weight monomers (Puckett et al., 2007). In 1962, Bowen synthesized bis glycidyl methacrylate from the combination of Bisphenol A and glycidyl methacrylate for use in dental composites. This monomer, also known as Bis-GMA or Bowen's resin, possesses high viscosity. Due to this high viscosity, the amount of filler particles that can be included is limited. In subsequent studies, triethylene glycol dimethacrylate (TEGDMA) was used as a diluent to reduce viscosity. This monomer combination has become one of the most commonly used matrix monomer combinations for dental composites to this day (Puckett et al., 2007).

Composite resins carry superior mechanical properties compared to acrylic and silicate materials, exhibit low thermal expansion coefficients, undergo less dimensional change during application, are resistant to wear, and their clinical performance is being improved (Ypei Gia et al., 2021). The initial composites were introduced to the market as two components that were mixed just before use and self-polymerized. This mixture often contained air bubbles, which negatively affected their durability (Bayne, 2013). While these precursor composites self-polymerized chemically, the next generation was polymerized with ultraviolet (UV) light. Subsequently, these materials were replaced by composite resins that polymerize with visible light. In recent years, there has been an increasing demand for restorations with superior aesthetics and improved mechanical properties. To meet this growing demand, the properties of tooth-colored restorative materials have been enhanced (Yu et al., 2008). Research on the resin matrix primarily involves the development of new monomers, while studies on the filler content include particle size, quantity, shape, and the development of new particles (Hosseinalipour et al., 2010; Mara da Silva et al., 2019).

Structure of Composite Resins

Composite resins fundamentally consist of three distinct components (da Silva et al., 2011; Yesilyurt et al., 2009):

- Resin matrix (Organic phase, carrier phase)
- Inorganic fillers (Inorganic phase, dispersed phase)
- Coupling phase (Interphase, silane agent)

Organic Matrix Phase (Resin Matrix Phase, Carrier Phase)

The organic phase consists of monomers, co-monomers, inhibitors, polymerization initiators, and ultraviolet stabilizers. The organic matrix of composite resins is essentially made up of mono-, di-, or tri-functional monomer systems. This monomer system can be considered the backbone of composite resins (Hervás-García et al., 2006). The most common monomers found in dental composite resins include bisphenol-A glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA), and bisphenol-A ethoxylate dimethacrylate (Bis-EMA) (Bociong et al., 2018).

Monomerler

Bisphenol-A Glycidyl Methacrylate (Bis-GMA), commonly referred to as Bowen's resin, is synthesized through a reaction between Bisphenol A and glycidyl dimethacrylate. It stands as the predominant monomer used in organic matrices (Chen, 2010). Characterized by its long-chain structure, Bis-GMA is a multifunctional monomer endowed with dual methacrylate groups, facilitating cross-linking in the course of polymerization. The hydroxyl groups present within the Bis-GMA structure account for the composite resins' water absorption and solubility traits. This absorption of water by Bis-GMA's hydroxyl groups induces polymer plasticization, weakening the material's chemical and mechanical integrity, and heightens its proclivity for discoloration (Camilotti et al., 2020). Additionally, Bis-GMA's notably high viscosity, stemming from hydrogen bonding among its hydroxyl groups and monomer molecules, limits the volume of filler particles that can be incorporated, thus necessitating dilution with alternative monomers for optimal use.

Urethane Dimethacrylate (UDMA): UDMA is a viscous and also high molecular weight monomer due to the intramolecular hydrogen bonding interaction between the amine (-NH-) and carbonyl groups (-C=O). However, due to the weak hydrogen bonding of the amine group compared to hydroxyl groups, UDMA exhibits much lower viscosity and higher flexibility compared to Bis-GMA. The absence of a phenol ring in UDMA's monomer chain contributes to a higher conversion and cross-link density compared to Bis-GMA, resulting in a more reactive structure and, consequently, a matrix that is more resistant to wear (Carvalho et al., 2012). The urethane configuration in the UDMA monomer incorporates amine functionalities, which are instrumental in facilitating unique chain transfer reactions. These reactions serve as an auxiliary route to sustain the polymerization process. Such mechanisms promote enhanced radical mobility which, in turn, leads to greater polymerization and heightened rates of monomer to polymer conversion.

Triethylene Glycol Dimethacrylate (TEGDMA): TEGDMA, which has the lowest viscosity among monomers, is added to reduce viscosity and enable the incorporation of more inorganic fillers into the structure. It also has the highest degree of conversion. This characteristic is achieved by increasing the number of cross-linking reactions during the polymerization of the resin matrix. While this monomer allows for an increased filler concentration, it also leads to an increase in polymerization shrinkage. Moreover, these monomers confer increased flexibility and lower wear resistance to composite resins. Additionally, the TEGDMA monomer increases the material's water absorption. Consequently, the inclusion of these monomers in the organic matrix can have both positive and negative effects on the properties of the composite (Borgia et al., 2019).

Bisphenol-A Ethoxylate Dimethacrylate (Bis-EMA): Bis-EMA was developed to provide biochemical stability due to its hydrophobic structure . Consequently, it results in the formation of a composite resin with lower solvent degradation, reduced water absorption, decreased polymerization shrinkage, and higher clinical durability (Stein et al., 2005).

Polymerization Initiators and Activators

The polymerization of composite resins occurs through an addition polymerization reaction, where monomers combine to form polymer chains (Zhou et al., 2019). For this polymerization reaction to initiate, the formation of free radicals is necessary. Once formed, these free radicals seek electron-rich monomers to create covalent bonds. The combination of these monomers results in the formation of a new polymer (30). In the organic resin matrix, the structures that generate free radicals are referred to as polymerization initiators; the structures that activate these initiators chemically or through light are called activators (Yazici et al., 2010). The role of initiator systems is to facilitate polymerization, thus solidifying the composite into a hardened mass (O'Brien, 2002). Polymerization of composite resins can be achieved chemically or through visible light activation. Dual cure is a combination of light and chemical polymerization. In chemically activated systems, free radicals that initiate the addition polymerization process are produced after an organic peroxide initiator reacts with a tertiary amine accelerator (Yazici et al., 2010). In light-cured systems, the polymerization initiator absorbs light energy emitted from the curing unit and reacts with the tertiary amine to produce free radicals, initiating the polymerization process. Although there are continuous advancements in developing various initiator systems for polymerization, the prevalent types of composites remain those that are light-activated using a singular initiator or those that are dual-cured, comprising a chemically activated component. The predominant photoinitiator system employed is camphorquinone, which is usually expedited by an aromatic tertiary amine. However, certain commercial mixtures incorporate alternative photoinitiators like phenylpropanedione (PPD), Lucirin TPO (monoacylphosphine oxide), and Irgacure 819 (bisacylphosphine oxide), known for inducing less yellowing than camphorquinone and thus enhancing color stability in the final composite restoration (Ferracane, 2011).

Ultraviolet Stabilizers

To minimize color changes caused by oxidation, UV absorbers can be added to composite resins (Craig, 1980). Compounds such as 2-hydroxy-4-methoxybenzophenone absorb ultraviolet wavelengths below 350 nm, ensuring color stability by mitigating the effects of UV light that could cause discoloration in the environment on the amine compounds in the initiator system (Hervás-García et al., 2006).

Inhibitors

To extend the shelf life of composite resins before polymerization and to ensure chemical stability after polymerization, a stabilizer or inhibitor such as hydroquinone monomethyl ether is used (24).

Color Pigments

To achieve a natural tooth appearance in composite resins, small amounts of inorganic oxides are added to provide a color and translucency similar to tooth tissue. Iron oxides are the most commonly used pigments for this purpose. This allows for a wide range of shades from very light tones to yellow and gray (Matsumoto et al., 2022).

In order to more closely replicate the natural luminescence of tooth enamel, composite resins may be blended with fluorescent agents. These substances, which are dyes or pigments, primarily absorb light within the ultraviolet and violet spectrums (usually between 340 to 370 nm) and emit it within the blue spectrum (commonly between 420 to 470 nm). Such additions are frequently employed to enhance the material's color perception, effectively creating a "whitening" impression and reducing the yellowish cast by amplifying the total reflection of blue light (Trigo-Humaran et al., 2022).

Inorganic Phase

To enhance the physical and mechanical properties of composite resins, inorganic fillers are incorporated into the organic resin matrix (Camilotti et al., 2020). Examples of these inorganic fillers include quartz, colloidal silica, barium/lithium aluminum silicate glass, borosilicate glass, and glasses of barium, strontium, aluminum, or zinc (Bociong et al., 2018).

Composite resins are made radiopaque by including elements with high atomic weights such as barium, strontium, zirconium, yttrium, aluminum, and silicon into the inorganic fillers (Bilgili et al., 2020).

In dental composite resins, the amount of inorganic filler typically constitutes 35-70% by volume or 50-85% by weight of the composite. Since filler particles are added to the organic matrix to improve the material's physical and mechanical properties, as high an amount of inorganic filler as possible should be included. Increasing the inorganic filler content consequently reduces the volume of the organic phase, minimizing polymerization shrinkage and shrinkage stress. There is a linear relationship between the elastic modulus and the inorganic filler load (Xu & Yang, 2019).

The mechanical properties of a composite material are significantly determined not only by the quantity of the filler particles used but also by their chemical compositions, morphologies, sizes, and methods of production (10,11). Flexural strength and modulus, hardness, and fracture toughness are influenced by both the morphology of the inorganic filler and the amount of inorganic filler loading (25). Beyond these, the presence of inorganic fillers brings benefits such as increased wear resistance, radiopacity; and decreased polymerization shrinkage, thermal expansion and contraction, water absorption, softening, staining; and finally, improved processability (Kim et al., 2024).

Binder Phase (Interphase, Silane Agent)

Achieving effective clinical performance in a composite demands the establishment of a robust interface between the inorganic filler constituents and the organic resin matrix through the curing process (28). This crucial interfacial bond is facilitated by employing organosilanes such as 3-methacryloxypropyltrimethoxysilane (MPTS) and 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) (Ge et al., 2023). Prior to integration with the oligomer, the silane agent is equipped with reactive functionalities on each terminus. In the course of polymerization, the silane’s vinyl groups engage with the polymeric matrix. Concurrently, the silane’s hydroxyl functionalities undergo condensation with hydroxyl groups present on the filler particles' surface, and on the flip side, they establish covalent linkages with methacrylate segments within the organic matrix phase (Rotariu et al., 2022).

The coupling phase plays a critical role in the composite. Its functions include the following (O'Brien, 2002):

- It creates an interface bridge that strongly binds the filler particles to the resin matrix.
- Enhances the mechanical properties of the composite and minimizes the separation of filler
- particles from the matrix during clinical wear.

- Provides a medium for stress distribution between adjacent particles and the polymer matrix.
- Offers a hydrophobic environment that minimizes water absorption of the composite.

Classification of Composite Resins

Table 1. *Classification of composite resins (Genç & Toz, 2017)*

Classification	Category	Details	Filler Content (%)	Particle Size (µm)	Method	Viscosity
Filler Particle Size	Megafill Composites	-	70-80	50-100	-	-
	Macrofill Composites	-	70-80	10-100	-	-
	Midifill Composites	-	75-80	1-10	-	-
	Minifill Composites	-	75-85	0.1-1	-	-
	Microfill Composites	-	35-60	0.01-0.1	-	-
	Hybrid Composites	-	70-80	0.04-1	-	-
	Nanofill Composites	-	72-87	0.005-0.01	-	-
Polymerization Method	-	Light-Cured	-	-	Light	-
	-	Chemically Cured	-	-	Chemical	-
	-	Heat-Cured	-	-	Heat	-
	-	Dual-Cured	-	-	Chemical and Light	-
Viscosity	-	Packable	-	-	-	High

Classification	Category	Details	Filler Content (%)	Particle Size (µm)	Method	Viscosity
	-	Flowable	-	-	-	Low

Classification of Composite Resins According to Inorganic Filler Particle Size

The most commonly used classification system for composite resins considers the size and distribution of filler particles. According to this system, composite resins can be classified into megafill, macrofill, midifill, minifill, microfill, hybrid, and nanofill composites (Alzraikat et al., 2018; Carneiro et al., 2016).

The size of filler particles in composite resins affects polishability/aesthetics, polymerization depth, polymerization shrinkage, and physical properties. Knowing the filler size and filler percentage in a specific composite will provide insights into the durability and polishability of the composite resin (Burgess et al., 2002).

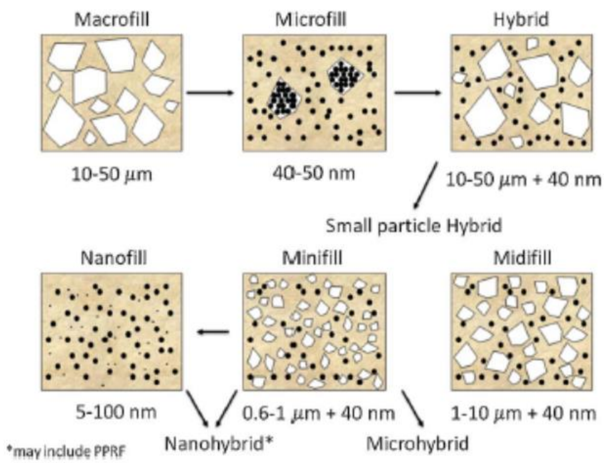

Figure 1. *Distribution of composite resins according to inorganic filler particle size (Ferracane, 2011)*

Megafil Composite Resins

In megafill composite resins, the size of the inorganic filler particles ranges from 50-100 μm. Additionally, glass particles sized 0.5–2 millimeters (mm), which are recommended for use in occlusal contact areas or in the restoration of worn areas and referred to as "inserts," are also considered as mega fillers (Andreasi Bassi et al., 2016).

Macrophile Composite Resins

Developed in the 1960s, macrofill composite resins feature filler particle sizes ranging from 10 to 100 μm. They are among the first composites developed, also known as traditional or large particle composite resins (Burgess et al., 2002). These composite resins contain large, spherical or irregularly shaped quartz and/or heavy metal glass particles. The resulting composites were quite opaque and had low resistance to wear (Ishida et al., 2019).

Macrofill composite resins have a relatively high filler content (approximately 75% by weight). Due to this high loading, these materials are quite hard, and the large size of the filler particles leads to two significant disadvantages. First, the filler particles are harder than the abrasives used for polishing, making these composites non-polishable. As these composite resins are polished, the relatively soft matrix wears away, exposing the large, hard fillers and resulting in a rough surface. This is a significant problem for a material intended to be "aesthetic." Secondly, the large filler particles can be "plucked out" from the surface of a posterior restoration by the cusps of opposing teeth, leading to immediate mass loss of the restorative material (up to 40 microns). The wear resistance of these materials is quite weak (Ritter, 2017).

Midifil Composite Resins

Midifill composite resins have inorganic filler particle sizes ranging from 1-10 μm. Due to their particle sizes, midifill composite resins are harder than microfill composites and can be polished better than macrofill composites. Midifill and macrofill composites are also referred to as traditional composites (Ismail et al., 2021).

Minifil Composite Resins

Minifill composite resins contain inorganic filler particles ranging in size from 0.1-1 μm. Compared to macrofill composites, the reduced particle size in minifill composites has allowed for an increase in the quantity of particles, resulting in a smoother surface than that of macrofill composites (Ruan et al., 2021).

Minifill composite resins include inorganic filler particles enriched with glass containing barium and strontium. These fillers provide radiopacity, increase resistance to wear, and achieve a smoother surface. These materials possess relatively higher durability and better polishability compared to midifill composite resins.

Microfiller Composite Resins

Developed in the 1970s, microfill composite resins contain spherical colloidal silica particles with sizes ranging from 0.01-0.1 μm (Bompolaki et al., 2022). Microfill composite resins were developed to provide a material with excellent polishability and aesthetics for restorative dentistry. These composites contain 35 to 67% by weight and 20 to 59% by volume of glass filler monomers (Mazer & Leinfelder, 1992). As a result, microfill composite resins, compared to composite resins with higher filler concentrations, result in a material with a lower modulus of elasticity, fracture resistance, and mechanical properties, making them unsuitable for stress-bearing restorations (Settembrini et al., 1993). However, pre-polymerized particles help maximize filler content and minimize polymerization shrinkage while making these composites highly polishable. This ensures they maintain a smooth surface during clinical wear (Ilie & Hickel, 2011). In microfill composites, the inorganic filler particles wear at the same rate as the organic matrix (Pagniano & Johnston, 1996). The good polishability of these composites results in aesthetic outcomes (Imamura et al., 1996). Due to these characteristics, microfill composite resins are indicated for Class V restorations, non-stress-bearing Class III restorations, and small Class I restorations. Due to their lower fracture resistance and potential for marginal breakdown, microfill composites are generally contraindicated for posterior stress-bearing restorations such as Class II and large Class I restorations (David et al., 2022).

Hybrid Composite Resins

Today, most composite resins used in dentistry fall under the "hybrid composites" category (Balkaya et al., 2019). This broad category includes traditional hybrids, micro, and nanohybrid composites. The term "hybrid" refers to the resin composite mixture containing submicron inorganic filler particles (0.04 μm) along with small particles (1 μm–4 μm). Hybrid composite resins were developed in the early 1980s by combining filler particles of different sizes to increase the wear resistance of composite resins and to ensure adequate polishability with an increased amount of inorganic filler (Nikaido et al., 2018). Although hybrid composite resins carry the characteristics of the different composite resins they contain, the type of hybrid is named after the particle that constitutes the highest percentage. If the percentage of microfiller particles is higher than other particles, it is called a microhybrid (36). Hybrid composite resins contain filler particles consisting of colloidal silica and glass particles made of heavy metals (Ai et al., 2024). These hybrid composite resins have a filler content ranging from 75% to 80% by weight. The use of a high amount and different sizes of filler particles improves the physical properties and aesthetics of the composite material. Characteristic features of these materials include good polishability, availability in various shades, increased wear resistance, and fracture toughness. These advancements make hybrid composites the preferred material for Class III and Class IV restorations. Additionally, their reduced polymerization shrinkage, low water absorption, improved durability, and wear resistance make them suitable for posterior stress-bearing cavities, such as Class I and Class II restorations. They have been proven to be viable materials for both anterior and posterior restorations.

Nanofil Composite Resins

Nanofill composite resins contain only nanoparticles as inorganic filler particles, with sizes ranging from 5 to 100 nm (0.005-0.01µm) (Alencar et al., 2020). Nanohybrid composites, on the other hand, contain a mixture of both nanosized and traditional filler particles (Alzraikat et al., 2018). The main filler material in nanofill composites is silicon dioxide, though borosilicates and lithium aluminum silicates are also commonly used. In many composites, heavy metal particles such as barium, strontium, zinc, aluminum, or zirconium, which are partly radiopaque, have replaced quartz. The inclusion of the smallest nanofill filler particles in restorative materials reduces the interparticle space in the organic matrix, thereby increasing the filler content. This increased filler content reduces the polymerization shrinkage of restorative materials, thus preventing marginal leakage, color changes, bacterial penetration, the presence of microcracks, and potential post-operative sensitivity at the restoration edges. Additionally, these fillers enhance wear resistance and improve mechanical properties such as stress durability and fracture resistance. With advantages in polishability, color stability, physical properties, and adequate oral longevity, these composites can be used in both anterior and posterior restorations (Asadian et al., 2021).

Nanofill composites can exist in two distinct forms: as isolated particles known as nanomers, which are approximately 5 to 100 nm in size, or as clusters referred to as nanoclusters. Nanomers consist of non-agglomerating silica or zirconia particles. The other type, called nanoclusters, is created by sintering nanomeric oxides to form clusters with a controlled particle size distribution. The primary particle size of the nanomers used to prepare nanoclusters ranges from 5 to 75 nm. These created nanoclusters are formed to have an average size of around 0.6 μm, although they can vary from 100 nm to sub-micron levels. Similar to how each grape in a bunch maintains its own form, nanomers within a nanocluster preserve their individual shapes (Estay et al., 2022).

Classification of Composite Resins According to Polymerization Types

Various initiation systems and activation methods can be used to generate the free radicals that initiate the polymerization process. The kinetics of polymerization have significant effects on the polymer structure. Consequently, the method of polymerization affects the properties of composite resins. Based on initiation systems or methods of polymerization, composite resins can be classified into chemically cured, light-cured, heat-cured, or dual-cured (both chemical and light) composites (Zhou et al., 2019).

Chemically Polymerized Composite Resins

The first composite resins were polymerized chemically. These composites are also referred to as chemically cured, autopolymerizing, or self-curing composite resins. Chemically cured composites consist of components that include a paste+liquid or paste+paste system, comprising a polymerization initiator and accelerator. The polymerization initiator commonly used is benzoyl peroxide (BP), and the polymerization accelerator is an aromatic tertiary amine activator (N,N-dimethyl-p-toluidine). When these two parts are mixed, free radicals generated from the reaction between BP and the amine subsequently react with monomers to initiate polymerization. These composites have a limited working time and, because they contain tertiary amines, they exhibit poor color stability over the long term, often yellowing or turning orange after several years of use (Ritter, 2017). For these reasons, most autopolymerizing composites are now primarily used not for direct restorations but as resin-based luting cements or core materials.

Light Polymerizing Composite Resins

Light-cured composite resins are subjected to polymerization through exposure to blue light within the 410–500 nm wavelength range, using a light-curing unit. Nowadays, nearly all dental restorative composites contain the initiation complex of camphorquinone (CQ) and a tertiary amine as the co-initiator, which polymerizes with visible light, a safer alternative compared to UV polymerization systems. The CQ/amine photoinitiation system operates differently from the BP/amine chemical initiation system.

When exposed to visible light, CQ absorbs energy to reach an excited state. In this high-energy triplet state, CQ interacts swiftly with the amine through an electron transfer to produce an energized complex, which then engages in hydrogen abstraction from the amine, leading to the formation of a novel entity. During this interaction, the excitation energy is passed to the amine, generating an α-amino-alkyl radical. This radical is considerably more effective in kick-starting polymerization compared to the relatively inert CQ-ketyl radical (Zhou et al., 2019).

For light-cured composite resins, polymerization is initiated using either ultraviolet (UV) or visible light (Tian et al., 2021). Currently, light sources for light-cured composite resins include halogen light sources, plasma arc light sources, laser light sources, and light-emitting diode (LED) light sources (Yu et al., 2018). The most commonly used are halogen and LED light sources. The use of LED light sources in dentistry began with the development of blue diodes in the 1990s. Research has shown that the depth of polymerization and the range of resin monomer conversion at an intensity of 100 mW/cm^2 are much better with LED light sources than with halogen light sources. The minimum energy required for adequate polymerization is 300 mW/cm^2 (Xia et al., 2023).

One of the most significant advantages of light-cured composites is the external control over the initiation of polymerization. This provides the possibility to shape the restoration before polymerization and ensures sufficient working time for shaping. Another advantage of light-cured composites is the achievement of color stability by eliminating tertiary amines (Ionescu et al., 2020).

Heat Polymerizable Composite Resins

Heat-cured composite resins are polymerized with external heat curing, which can help reduce the amount of residual monomer. This reduction in the residual monomer content leads to improvements in the mechanical properties of the composite resin (Tezvergil et al., 2005).

Composite Resins that Polymerize Both Chemically and with Light

Materials that utilize both chemical and light polymerization technologies are referred to as dual-cure composite resins. In these composites, the polymerization reaction is initiated by exposure to visible light, but the reaction continues slowly over time even in the absence of light. These composite resins are commonly used for the cementation of endodontic posts and as core materials (Elawsya et al., 2022).

Classification of Composite Resins According to Their Viscosity

Composite resins can be classified based on their viscosities. Universal restorative materials can have different consistencies depending on their formulations, allowing them to be placed with the help of a syringe or hand instrument (Schwendicke et al., 2018).

Recoilable (Condensable) Composites

Packable (condensable) composites were developed in the late 1990s as an alternative to amalgam for use in posterior restorations. These composites are more viscous and less sticky compared to traditional composites. The increase in viscosity is achieved by increasing the size of inorganic particles, incorporating fibers, and increasing the percentage of inorganic fillers. Thanks to the increased viscosity, they are easier to shape and facilitate achieving tight interproximal contact compared to traditional composites. For these reasons, the main indications for packable composites are Class II cavities (Cui et al., 2020).

The physical properties of packable composites are not superior to those of traditional hybrid composite resins. Their main disadvantages include difficulty in achieving cohesion between layers of composite during layering, reduced wear resistance due to the large size of inorganic filler particles, and poor aesthetics in anterior teeth (Gazzotti et al., 2022).

Fluid Composites

Flowable composites were first introduced to dentistry in 1996. Generally, flowable composites are produced with lower viscosity either by reducing the filler content from 50-70% by volume to 37-53% (Burgess et al., 2002) or by adding modifying agents such as surfactants to increase flowability. The viscosity is reduced and flowability increased, allowing these composites to be easily applied to the small edges or corners of a cavity using an injection technique.

The advantages of flowable composites include high wettability, which allows them to easily penetrate into every irregularity; the ability to form minimal thickness layers that prevent air bubble formation; low modulus of elasticity providing ease of use in stress-concentrated areas; high flexibility; and a variety of color options (Asadian et al., 2021). The disadvantages include a lower inorganic filler ratio leading to increased polymerization shrinkage, and a decrease in wear resistance, physical, and mechanical properties.

First-generation flowable composites, due to their lower filler contents and lower elastic moduli, were used only as liners or pit and fissure sealants. However, with the development of organic resin matrices and inorganic fillers, new-generation flowable composites have a broader application area. They are used in minimal invasive cavity preparations, cervical caries, abrasion/abfraction lesions, and the repair of composite restorations, among others . In addition to these applications, their most common use is as a stress-relieving base material of 0.5 mm thickness applied to the cavity floor after the adhesive system, especially in large posterior group cavities. This is to eliminate potential gaps and the side effects of stresses related to the polymerization shrinkage of composite resins (Chatzistavrou et al., 2018).

New Developments in the Structure of Composite Resins

Self-Adhesive Composite Resins

When comparing directly placed materials like amalgam to composite resins, one of the primary disadvantages of composites is the technical sensitivity of the restorative procedure. To simplify the composite restoration application process by eliminating the most sensitive step of adhesive application, self-adhering composite resins were developed. All produced self-adhering composite resins are of a flowable consistency, designed as materials to enhance adaptation in the initial layer due to their low viscosity. The composition of these dental materials features monomers with self-etching and/or self-adhesive properties, enabling them to etch or create chemical bonds with the surfaces of enamel and dentin. These include compounds such as 4-methacryloxyethyl trimellitic acid (4-MET), glycerol phosphate dimethacrylate (GPDM) monomers, and 10-

methacryloyloxydecyl dihydrogen phosphate (10-MDP) among others. Specifically, the GPDM monomer, via its acidic phosphate group, constructs a microretentive surface on dental tissues, facilitating a chemical bond with the calcium present in the tooth's hard tissue. Simultaneously, the methacrylate groups at its opposing end are capable of initiating cross-linking and copolymerization with other monomers, resulting in the formation of a robust network structure (Fugolin & Pfeifer, 2017).

Research indicates the presence of micromechanical bonding between polymerized monomers and the partially demineralized collagen fibrils. Yet, recent studies have revealed that the bonding strength of resin-based self-adhesive restorative flowable composites doesn't reach the levels achieved when adhesive and composite are applied individually to the tooth's structure. Consequently, research and clinical evaluations are needed for self-adhesive composites. Self-adhesive composite resins can be used as liners in minimally invasive intervention cavities or in Class II cavities (Liu et al., 2023).

Conclusion

In concluding the chapter on "Composite Materials in Restorative Dental Treatments," it is imperative to acknowledge the significant advancements that composite materials have introduced to the field of restorative dentistry. From a restorative dental treatment practitioner's perspective, the evolution of composite resins has enabled the delivery of aesthetically superior and functionally durable dental restorations. These materials have not only revolutionized the way restorative treatments are approached but have also significantly improved patient satisfaction and treatment outcomes.

The development of self-adhering composite resins and the continuous improvement in the formulation of composite materials have simplified the restorative procedure, reducing technical sensitivity and potentially decreasing chair time. This advancement underscores the importance of ongoing research and clinical evaluations to optimize the performance and application techniques of these materials. Despite the challenges associated with the bond strength of resin-based self-adhesive restorative composites, the benefits of minimal invasiveness and the ability to achieve aesthetically pleasing results cannot be overstated.

As restorative dental treatment practitioners, it is crucial to remain abreast of the latest advancements in composite materials and to continue honing our skills in their application. The commitment to evidence-based practice and continuous learning will ensure that we can provide the best possible care to our patients, leveraging the advancements in composite materials to achieve restorations that are not only aesthetically pleasing but also durable and biocompatible.

In summary, composite materials have transformed restorative dental treatments, offering solutions that are in line with the principles of conservative dentistry while providing excellent aesthetic and functional outcomes. The future of restorative dentistry will undoubtedly see further innovations in composite materials, and it is our responsibility as dental practitioners to integrate these advancements into our practice, enhancing the quality of care we provide to our patients.

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CHAPTER III

Optıcal Properties Of Composite Resıns

Özge DUMAN[1]

1.1 Introduction

One of the most important goals of aesthetic restorative dentistry is to produce restorations that match the optical characteristics of natural teeth. Color, translucency, fluorescence, opalescence, and opacity are optical properties that give dental materials the ability to mimic the vibrant appearance of a tooth (JM, 2006,) (Yu B, 2009).

1.2 Composite Resins

Composite resins are frequently selected as direct restorative materials. They offer significant advantages such as aesthetic appeal, blending well with natural tooth structure, and the ability to bond

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effectively to the tooth, which helps reinforce and strengthen it (Roberson TM, 2006).

Composite resins mainly consist of 3 main components. These components are resin matrix, inorganic fillers, and coupling agent.

In addition to these main components, polymerization initiators and accelerators can be added in small amounts of inorganic oxide pigments to obtain various shades (Mitchell, 2008).

1.2.1 Organic Resin Matrix Phase

The organic resin matrix phase consists of a blend of monomers with varying chain lengths that chemically combine to create a durable material. Since the early 2000s, there has been a notable emphasis on developing more specialized methacrylates. These include Bis-GMA (bisphenol A glycidyl dimethacrylate), TEGDMA (triethylene glycol dimethacrylate), Bis-EMA (ethoxylated bisphenol A dimethacrylate), and UDMA (urethane dimethacrylate). These methacrylates contribute to the properties and performance of composite resins used in dental restorations (Feng L, 2010).

The most commonly used material in dental materials, Bis-GMA, has a central phenyl ring core and two hydroxyl groups. The hydroxyl group is responsible for the extremely high viscosity and low mobility of Bis-GMA, which is its major disadvantage. At the same time, the hydroxyl group also contributes to high water absorption (S. Kalachandra, 1991).

The polar bonds present in the chain structure of TEGDMA monomer are weak and flexible. Therefore, it has a very low viscosity relative to the Bis-GMA monemer. For this reason, it is used for the purpose of diluting the composite material. It also allows denser filler particle placement. The disadvantage of TEGDMA is that it increases the water absorption of the material, has low color stability and negatively affects the mechanical properties (Shiv Ranjan Kumar, 2015).

Bis-EMA is formed by ethoxylation of the Bis-GMA monomer (substitution of ethoxy groups by one of the hydroxyl groups). The primary advantages of Bis-EMA include its low viscosity, minimal water absorption, and reduced polymerization shrinkage. Thanks to its low viscosity, Bis-EMA can also be used as a diluent of composite materials such as TEGDMA.

HEMA, a hydrophilic monomer, is an important component of the adhesive system. Thanks to its hydrophilic feature, it can easily wet the moist dentin surface. UDMA monomer has a lower viscosity than Bis-GMA monomer and a higher viscosity than TEGDMA. For this reason, in recent years, many composite materials have been replaced by Bis-GMA (A. Khatri, 2003).

Most composite resins are based on Bis-GMA or UDMA. Other resins used to modify viscosity and use include TEGDMA and bisphenol-A-polyethylene glycol dieter dimethacrylate. However, the greater the proportion of these "diluent" monomers, the greater the polymerization shrinkage, increasing the risk of micro-leakage with marginal void formation (Anusavice, 2012) (Mitchell, 2008)**.**

1.2.2 Inorganic Filler Phase

Various fillers such as silicon dioxide, aluminum oxide, barium, zirconium oxide, borosilicate, and barium aluminum silicate glasses are commonly incorporated into composite resins. The inorganic filler phase plays a crucial role in enhancing the mechanical properties of the composite material while also reducing polymerization shrinkage and the thermal expansion coefficient.

The size, shape, and quantity of these inorganic filler particles significantly influence both the mechanical and physical properties of composite resins. Increasing the amount of filler particles generally improves the overall physical and mechanical performance of the material. A higher filler content enhances wear resistance, hardness, and reduces the thermal expansion coefficient.

As the volume ratio of filler particles in the composite material approaches approximately 70%, the material's wear and fracture resistance levels can become comparable to those of natural tooth structure. Additionally, in order to achieve a semi-transparent appearance similar to enamel, the material allows light to pass through and scatter (Anusavice, 2012) (Mitchell, 2008) (Dayangaç, 2011)**.**

As filler particles increase in volume, the proportion of organic matrix decreases, leading to reduced polymerization shrinkage in composite materials. Additionally, this adjustment contributes to advantages such as lowered coefficient of thermal expansion and decreased water absorption (Anusavice, 2012) (Roberson TM, 2006)**.**

The shape, size and content of the filler particles are as effective as the ratio of the amount of inorganic filler to volume, as well as the properties of the material. And during the development of composite materials, many changes have often been tried.

Initially, composites containing macrofillers with a size of 50-100 μm were produced. However, at the end of the 1970s, composite resins containing micro fillers were introduced to the market. This innovation has provided advantages such as much better polishability of the material and lower color change (JM, 2006,) (Powers, 1980).

However, the decrease in the rate of inorganic fillers caused the inadequacy of mechanical properties. For this reason, it has been tried to add pre-polymerized filler particles into the organic matrix in order to improve the mechanical properties. However, since the pre-polymerized filler particles were not covalently bonded to the matrix, it caused the wear resistance to be low (Ferracane J. , 1995).

In the early 1980s, hybrid composites were produced. In this way, it is aimed to ensure that the advantages of composites with macro and micro filler content can coexist.

In the first versions of dental composites, quartz was mostly used as a filler. However, since it is a very hard material, it has been replaced by silica, which is less hard than quartz, due to the fact that it causes abrasions on the opposite tooth and its polishing is difficult. Instead of the hard crystalline form of silica, the less hard non-crystalline forms are used. Again, inorganic fillers such as barium, yterbium, yttrium trifluoride were added instead of quartz due to its high radiopacity and fluorite release (Miletic, 2018).

Numerous research studies indicate that the filler content, size, and morphology in composite resin formulations significantly impact various properties. These include mechanical strength, polymerization shrinkage reduction by decreasing monomer content, wear resistance, translucency, opacity, radiopacity, and surface roughness (Salazar, 2013) (Turssi, 2005) (Lee Y. K., 2008).

Spherically symmetrical nanofillers, with diameters smaller than the wavelength of visible light (less than approximately 380 nm), can generate angle-independent structural colors without requiring pigments. Silicon dioxide (SiO2) particles ranging from 200 to 300 nm in diameter can produce a variety of structural colors (Franklin D, 2020). Studies have reported a negative correlation between increasing filler content and light transmittance in composite materials (Fronza, 2017).

1.2.3 Silane Coupling Agent

The silane coupling agent acts as a mediator that bonds inorganic filler particles to the organic resin matrix through silane groups. This integration ensures that the organic resin matrix and the inorganic filler phase behave as a cohesive unit, enhancing the overall performance and durability of the composite material. It increases mechanical strength, prevents water passage, and reduces water absorption and solubility (Roberson TM, 2006).

In numerous composite resins, the molecules feature silanol groups at one end and methacrylate groups at the other end. The hydroxyl group at the probe end binds to inorganic filler particles, while the methacrylate group binds to the resin matrix (Roberson TM, 2006).

1.3 Optical Properties

1.3.1 Light

Visible radiation, also known as light, belongs to the electromagnetic spectrum, which encompasses a range of energies including radio waves, X-rays, ultraviolet (UV) rays, and infrared (IR) radiation (Berns, 2019).

Understanding optical aesthetics begins with comprehending the physical properties of light. Light consists of particles known as photons, which are manifested as electromagnetic waves of varying wavelengths (Villarroel, 2011).

Visible light is a blend of various wavelengths and is commonly referred to as white light. The human eye can detect these wavelengths, leading to the term "visible light spectrum." Physically, visible light wavelengths range approximately from 400 to 700 nanometers (nm). Each color tone is precisely defined by its specific wavelength or frequency (Chu., 2004). Monochromatic light is characterized by having a single wavelength or color, resulting from energy emitted at short wavelengths. When monochromatic light interacts with matter, the path of its rays can be regular, diffuse, or a combination of both (Villarroel, 2011).

The reflection of light on a flat surface is termed specular or regular reflection. In this type of reflection, the angle of incidence equals the angle of reflection. Conversely, light reflecting off rough surfaces exhibits diffuse reflection. Here, the surface behaves like a multitude of irregularly positioned surfaces, causing rays to scatter in various directions rather than in a parallel manner (Halliday, 2013).

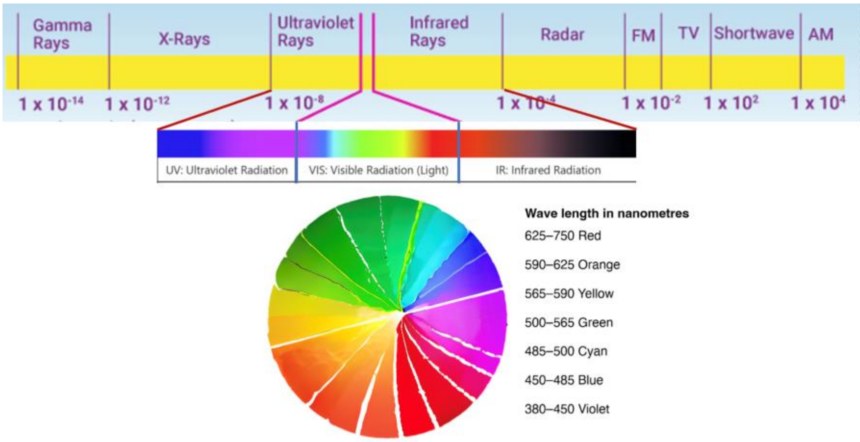

Fig.1; Light Spectrum

1.3.2 Color

Four outcomes result from the interaction between light and an object: (1) specular reflection, where light reflects sharply off the object's surface; (2) diffuse reflection, where light scatters uniformly from the surface; (3) absorption and scattering of light within the object's structure; and (4) transmission, where light passes through the object.

The light that reaches the observer's eyes as a result of these interactions carries color information about the object (Oscar E. Pecho, 2016).

Some wavelengths of light will be absorbed if the light encounters molecules or larger particles in the material. The number of light rays absorbed and their specific wavelengths (colors) are determined by the density and structure of the material through which the light passes; transmitted wavelengths (called spectral data) make up the perceived color (Chu., 2004).

Wavelengths of light that are not absorbed (reflected, transmitted, or emitted directly into the eye) are detected by receptor cells in the eye known as rod and cone cells. Rod cells are responsible for peripheral vision and do not perceive color; they assist in seeing objects in grayscale under low light conditions. As light levels increase, rod cells become less active. In contrast, cone cells function in bright light conditions and provide color vision with high acuity. Both types of photoreceptors convert light into chemical signals that stimulate millions of nerve endings. Neural signals are transmitted via the optic nerve to the brain, where color and visual information are interpreted (Roberson TM, 2006).

Sunlight, specifically daylight with the CIE standard illuminant D65, is commonly regarded as the standard for accurate color assessment. However, its variability necessitates cautious use. In dental offices or laboratories, other common light sources include incandescent lamps and fluorescent lamps, each characterized by distinct spectral distributions (Yu, 2009).

Another concept related to color is metamerism. This phenomenon refers to the perception of dental materials and tissues displaying different color tones under varying light sources. Objects that appear identical in color under one light source may appear differently when observed under another light source. This phenomenon is called "metamerism," and the two objects involved in the phenomenon are referred to as a "metameric pair" (Paravina ve Powers, 2004; Chu ., 2004).

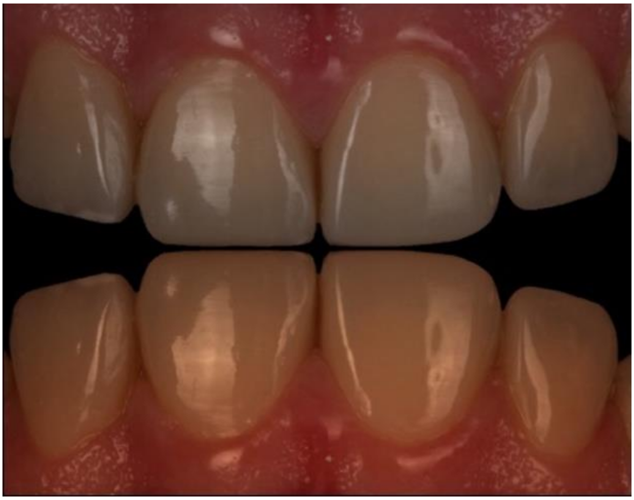

Fig. 2 : Metamerism

In reality, among all visible colors and tones, there are three primary colors: red, green, and blue (sometimes referred to as violet). Every other color can be created by combining these primary colors in the right proportions. For instance, yellow light is a blend of green and red lights (Sakaguchi RL, 2012). Color perception is influenced and perceived through factors such as color hue and intensity, translucency, fluorescence, opacity, light transmission and scattering properties, surface texture, and gloss.

Color perception is not solely determined by its inherent color dimensions and optical properties but is also influenced by environmental conditions, the adaptation of our eyes, and our prior visual experiences. Objects of identical color can appear differently due to phenomena known as chromatic induction. Chromatic induction can lead to either a contrast effect or an assimilation effect. Simultaneous color contrasts occur when the color of an object shifts towards its complementary color, creating a noticeable difference. In contrast, chromatic assimilation occurs when the perceived difference between the object's color and its surroundings diminishes (Roberson TM, 2006).

Clinically, perceptual assimilation occurs when a restorative material (the object) takes on the color of the surrounding tooth (background/environment), creating a more harmonious and blended appearance than when viewed independently. In dental literature, this visual phenomenon is referred to as the Blending Effect, where the dental and restorative materials visually merge. It's worth noting that the blending effect is sometimes incorrectly labeled as the "chameleon effect." (Trifkovic, 2018,) (Paravina, 2006).

The color appearance of dental restorations can be influenced by environmental colors, known as color shift. Two terms describe this phenomenon: simultaneous contrast, where the perceived color difference increases between an area and its surroundings when viewed together compared to separately, and blending (color assimilation, color induction, Von Bezold's color mixing effect, or Von Bezold's spreading effect), where the perceived color difference decreases when viewed together compared to separately (Paravina, 2006) (Shinoda, 2004) (Pridmore, 2004).

A wide variety of color identification systems have been used from past to present. Munsell color system; Color perception is defined by three objective variables: Hue, Value, and Chroma. These three parameters make up the three dimensions of the color space (Kenneth J. Anusavice, 2021).

Hue, often synonymous with tone, refers to the basic color of an object such as red, green, or yellow. It is determined by the wavelength of reflected or transmitted light that is observed. The position of the wavelength (or wavelengths) within the visible spectrum determines the specific hue of a color. Shorter wavelengths correspond to hues closer to the violet end of the spectrum, while longer wavelengths correspond to hues closer to the red end. In dentistry, hue describes the primary pigments (e.g., red, blue, yellow) present in a natural tooth or a tooth restoration (Wee A. G., 2006,). (Chu., 2004).

Chroma, sometimes referred to as saturation, denotes the intensity or purity of a specific hue or the concentration of pigment. It relates to how vivid or dull a color appears. In dental literature, these terms are often used interchangeably to describe the strength or richness of a particular color tone (Roberson TM, 2006).

The purity or saturation of excitation of a color defines the degree to which it differs from the achromatic perception of color, which is most similar to it. The numbers that represent the purity of arousal range from 0 to 1. This quality of color perception is known as chroma (JM, 2006,) (Wee A. G., 2006,)

Value; It is defined as brightness. According to Munsell, value is a black-and-white scale. On this scale, 0 indicates black and 10 indicates white. The greater the total amount of light reflected, the higher the valu (Munsell, 1961).

The CIELab color system, established by the International Commission on Illumination (CIE) in 1976, differs from the Munsell color system by utilizing three parameters: L*, a*, and b* to define colors. This system offers the advantage of being an approximately uniform three-dimensional color space where the elements are evenly spaced based on visual color perception. Each unit change in the L*, a*, and b* parameters is perceived as approximately equal, allowing for more precise and consistent color representation and measurement (Della Bona, 2003).

L* is similar to value in the Munsell system and represents the lightness, brightness, or black/white character of the color, while the coordinates a* and b* define the chromatic properties of the color. a* is the red (+)/green (-) coordinate and b* is the yellow (+)/blue (-) coordinate (Wee A. , 2006).

Three color difference formulas—CMC, CIE94, and CIEDE2000—have been developed based on the CIELab formula over time (Ghinea M.´., 2010).

The CIEDE2000 formula was published by the CIE (International Commission on Illumination) in the year 2000. It has a much more complex formula system than other color difference determination formulas. CIEDE2000 is based on the CIELab color system (G. Sharma, 2005).

Most of the studies have shown that there is a correlation between the calculations made with the CIELab formula and those made with the CİEDE2000 formula. However, he did not show that the two formulas can be used interchangeably (Ghinea M.´., 2010).

To address limitations in the CIELab color space, the CIEDE2000 formula incorporates several corrections. These include weighting functions (SL, SC, SH) to adjust for perceptual sensitivity, a rotation term (RT) to minimize interactions between color and hue differences in the blue region, adjustments to the a* axis of CIELab for improved accuracy with neutral colors, and parametric factors (KL, KC, KH) to account for different experimental conditions (Luo MR, 2001). The CIEDE2000 weighting functions (SL, SC, SH) and parametric factors (KL, KC, KH) have been said to result in better alignment in visual evaluations (Luo MR, 2001). The CIEDE2000 weighting functions (SL, SC, SH) and parametric factors (KL, KC, KH) are designed to improve accuracy in visual evaluations of color differences (del Mar Perez, 2011).

Recent studies indicate that the CIEDE2000 color difference formula offers improved accuracy in assessing visual tolerances compared to the CIELAB formula. These findings support its application in dentistry and other fields requiring precise color evaluation (Wee A. G., 2007) (Ghinea R. P., 2010).

1.3.3 Whiteness index

From a spectral perspective, whiteness is defined as a material with consistent and high reflectance, typically nearing 100%, across the entire visible wavelength spectrum. Whiteness is perceived as one-dimensional, characterized by high light reflectance and low purity. It occupies a relatively narrow region in the color space, primarily along dominant wavelengths around 570 nm and 470 nm as proposed by Ganz. In the CIELAB color space, this spectral characteristic translates to very high lightness (L*) and ideally zero chroma (a* and b* values), indicating a color that is extremely light and devoid of chromaticity (Bona, 2020).

1.3.4 Scattering and Absorption

When light interacts with matter, it can undergo scattering. This phenomenon involves some of the light being absorbed and re-emitted at the same wavelength, while other portions of light scatter in various directions. This scattering causes light to travel in different directions, contributing to the diffusion of light across various paths (Rocha RS, 2017).

Absorption is the process by which light is taken in by a material. When light interacts with a substance, it can either pass through (transmitted), be absorbed (where its energy is taken up by the material), or be lost through reflection or scattering. If a material absorbs certain wavelengths of light while allowing others to pass through, it may appear colored yet somewhat transparent. For instance, colored glass absorbs specific colors of light while transmitting others. On the other hand, if a material absorbs all wavelengths of visible light equally, it appears black and is considered opaque because no light passes through it (Rocha RS, 2017). A blue surface reflects primarily the blue portion of light and absorbs most of the other colors (Bona A, 2019).

Rayleigh scattering of light refers to specific relationships between particle sizes and light scattering. When light encounters small particles, it scatters differently compared to its reflection in the surrounding environment. The degree of scattered light primarily hinges on the disparity between the refractive index of the particles and that of the medium surrounding them. If the particles and their medium possess similar refractive indices, light scattering is minimal, and the boundary between them is indistinct (Berns, 2019). Small particles scatter a small amount of light initially. As the size of the particles increases, light scattering also increases until it reaches a point where it maximizes around the wavelength of light. Beyond this point, for larger particles, light scattering decreases. This phenomenon is observed due to how different sizes of particles interact with incident light, affecting the scattering pattern and intensity (Tabatabaei, 2019).

Scattering and absorption are the primary optical properties that influence the propagation of optical radiation through a material. While both phenomena play significant roles, scattering is generally considered to have a greater impact on how optical radiation propagates within the material. This is because scattering alters the direction of light without necessarily reducing its intensity, whereas absorption absorbs and converts light energy into other forms such as heat, thereby reducing the intensity of light passing through the material (Bona, 2020).

1.3.5 Transmittance and Refraction

The almost complete passage of light through a material can be defined as transmittance (Chu., 2004). Transmittance is measured by the ratio of the intensity of the light passing through the material to the intensity of the incident light, as explained (Bona, 2020).

A small amount of reflected light is due to the slowing down of light inside the material. Refraction, denoted by the refractive index, is used to describe the bending or breaking of light due to a change in speed apart from a change in speed. When a spoon is placed halfway into water in a glass, it appears to be bent when viewed from the side (Berns, 2019).

Wavelength dependency describes how light disperses into a spectrum when passing through a prism. Upon encountering a surface, reflections typically have polarization parallel to the surface. Specific angles are calculated using Snell's law as light refracts upon encountering a material with a different refractive index. The intensity of refracted light is determined by subtracting the intensity of reflected light from the incident light. For example, in window glass, which typically has a refractive index around 1.5, approximately 90% of light passes through while the rest is reflected or absorbed (Tilley, 2011).

1.3.6 Opacity

The prevention of light passing through a material. The material absorbs some of the light while reflecting some (JM, 2006,) (Anusavice, 2012). Translucency and opacity are related to a material's ability to transmit light (Bona, 2020).

The hiding power or opacity of materials is defined by the contrast ratio (CR) for industrial applications. Dental material opacity was defined by Paffenbarger and Judd in 1937, but it was not until 1979 that composite restorative materials known as "aesthetic dental fillings" were developed (Judd, 1937,) (Crisp, 1979).

It has been observed that materials with high scattering and absorption coefficients limit the ability of contrast ratio (CR) to detect small changes in light transmission. Therefore, CR is typically suitable only for materials that maintain a minimum total transmission percentage of at least 50%. This justifies the preference for total luminous transmission (TP) over CR, as TP is more commonly used to evaluate the ability of materials to mask colorless substrates in dental studies (Spink, 2013).

1.3.7 Opalescence

Small changes in each wavelength band of a beam of light significantly affect color and appearance (Bona, 2020). Opalescence occurs when there is light scattering, particularly at shorter wavelengths within the visible spectrum. This phenomenon results in a material appearing bluish when observed under reflected light and orange or brown when observed under transmitted light (Arimoto, 2010).

1.3.8 Fluorescence

Fluorescence is the process where a substance absorbs light at shorter wavelengths and then emits light at longer wavelengths, often in the visible spectrum. This emission typically results in the substance appearing brighter and more vibrant compared to non-fluorescent substances, which only reflect the visible light that falls on them without emitting light themselves. Fluorescence occurs when certain wavelengths of radiation are absorbed by the substance and re-emitted at shorter wavelengths (Mualla, 2016).

It is when dental material/tissue emits light to its surroundings after receiving high energy. Radiation stops after the incoming light is interrupted (Chu, 2004).

Human teeth are naturally fluorescent, a property known as autofluorescence, because their dental tissues readily absorb UV light. When exposed to UV light (between 350 and 400 nm), these tissues absorb the light and then re-emit it at longer wavelengths within the visible spectrum (between 410 and 500 nm). Both enamel and dentin exhibit autofluorescence, though enamel's fluorescence is relatively weak due to its low organic content. Typically, teeth appear bluish-white when viewed under UV light.The fluorescence spectrum of natural enamel shows peak luminescence around 450 nm, while dentin exhibits peak luminescence at 440 nm (Volpato, 2018).

1.3.9 Translucency

Translucency is a crucial factor in determining the aesthetics of restorative materials and plays a significant role in material selection. In aesthetics, translucency affects how light interacts with the material, influencing its visual appearance. The human eye is particularly sensitive to changes in value (lightness or darkness) rather than changes in color or hue alone. Therefore, achieving the right balance of translucency is essential in creating natural-looking dental restorations that harmonize with surrounding natural teeth (Bona, 2020) (Lucena, 2021).

A translucent material allows light to partially pass through it, absorbs some of the remaining light, and reflects light from its surface or internal interfaces. Ceramics and composite resins used in dentistry are examples of translucent materials. These materials are selected for dental restorations because their translucency mimics the optical properties of natural teeth, contributing to a more natural appearance when light interacts with them (JM, 2006,) (VAN NOORT & BARBOUR, 2014.).

Translucency is especially critical for tooth enamel. The average total luminous transmission (TP) values for human enamel and human dentin are approximately 18.7 and 16.4, respectively. Translucency varies with wavelength, but simplifying the translucency spectrum (CR values at different wavelengths) to a single parameter (TP) offers a straightforward method to compare translucency across materials. This single parameter helps in evaluating how much light is transmitted through the material overall, providing a clearer understanding of its translucency characteristics (BIN YU, 2009).

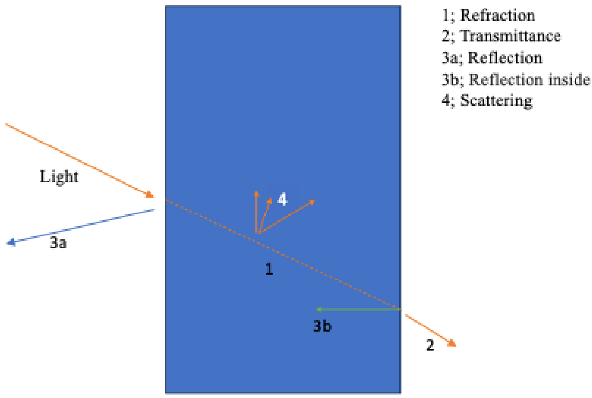

Fig. 4 ; Interaction between light and materials

In 1948, Kubelka and Munk introduced a simplified mathematical model to describe the interaction of light with translucent materials. This model is highly relevant in dentistry, given that both natural dental tissues like dentin and enamel, as well as dental materials designed to mimic them, exhibit translucency.The significance of the Kubelka-Munk theory lies in its ability to relate scattering and absorption coefficients to the material's reflectance and transmittance properties. This provides a quantitative framework to understand how light interacts with and penetrates through dental materials, aiding in the evaluation and development of aesthetic restorative materials in dentistry (Bona, 2020).

1.3.10 Surface Texture

The brightness or matte appearance of a material is determined by the smoothness of its surface. Enamel, for instance, appears shiny because its surface is exceptionally smooth, allowing it to reflect most incident light. In contrast, as the surface roughness increases, light is scattered more diffusely, leading to a matte appearance. This distinction is crucial in restorative dentistry because the appearance of a restored tooth can be affected if the restoration's surface is matte and differs noticeably from the natural tooth structure. Therefore, achieving a smooth surface texture for dental restorations is important for maintaining a seamless aesthetic integration with the surrounding natural teeth (Noort, 2013).

Surface gloss is an optical property and is important in color perception. Gloss is a visual aspect of the appearance of surfaces that results from the geometric distribution of light reflected from surfaces (Lee Y. K., 2002) (Roberson TM, 2006).

On smooth and polished surfaces, light behaves predictably: when the angle of incident light equals the angle of reflected light, the reflection is specular, resulting in high gloss. However, on rough surfaces, light is scattered in multiple directions due to surface irregularities, which reduces glossiness. Achieving high gloss is therefore easier on smooth surfaces where light reflects uniformly and predictably, contributing to a polished and shiny appearance (Sengez, 2019).

Smooth surfaces reflect light more efficiently, giving a brighter appearance. Correlation studies between gloss and roughness have shown that gloss tends to decrease with increasing roughness parameters. However, studies have also shown that roughness alone is not effective in surface gloss, and that surfaces with roughness down to 1 μm can still be seen as glossy (Chung, 1994) (Ereifej, 2012).

1.4 Optical Properties of Composite Resins

Optical properties are crucial for achieving aesthetic restorations that resemble natural tooth structure using composite resins. The most defining optical properties are translucency and color.

Nanofillers used in modern composite resins range in size from 1 to 100 nm, which is smaller than the wavelength of visible light (380-780 nm). This characteristic enables the production of highly translucent materials that do not scatter or absorb visible light significantly. Two types of nanofillers have been synthesized for these nanocomposites: nanometric particles (nanomers) and nanoclusters. Nanomers are primarily composed of monodisperse, non-agglomerated zirconia (2-20 nm) or silica particles (2-75 nm) (Chen, 2010) (Pecho, 2016). Due to their small particle size, nano-filled composite resins exhibit excellent resistance to wear and fracture, along with good formability. They also offer significant advantages in terms of optical properties. Nano fillers contribute to low opacity in dental composites that resist staining, enabling a broad spectrum of hues and opacities to be achieved (Ferracane J. L., 2011) (Pecho, 2016).

1.4.1 Scattering, Absorption and Reflection in Composite Resins

The translucency and color of a resin composite are influenced by two wavelength-dependent parameters: the absorption coefficient (K) and the scattering coefficient (S). As the scattering coefficient (S) decreases gradually, the absorption coefficient (K) tends to decrease sharply with increasing wavelength. The refractive index (RI) of the material increases as the scattering coefficient (S) increases and the absorption coefficient (K) decreases. RI values also tend to increase with wavelength. In commercial resin composites, the change in absorption coefficient (K) with wavelength has a greater impact compared to the change in scattering coefficient (S). Light reflection, which is the reflection of light from a material of infinite thickness, can accurately represent the true color of a semi-transparent material regardless of its thickness (Lee., 2007).

Using Kubelka-Munk equations, it is possible to determine the scattering coefficient, absorption coefficient, and light reflection coefficient for various shades of resin composites. This allows for a detailed understanding of how these materials interact with light and contribute to their optical properties (Lee., 2007).

Scattering varies according to the wavelength of the incident light and is mostly determined by particle size. Absorption and reflection also vary with the wavelength of the incident light and the nature of the colorant pigments (Lee., 2007). The refractive index of pigments differs from that of resin, and their diameters are typically close to the wavelength of light. When pigments are very small and have a refractive index similar to resin, they scatter only a small amount of light, resulting in semi-transparency. Therefore, controlling light scattering can be achieved by selecting pigments with specific sizes and refractive indices. To enhance translucency, pigments can be coated with iron oxide to minimize the refractive index difference between pigments and resin. Instead of focusing solely on refractive index differences, the size of organic pigments can also be adjusted to control light scattering effectively. Even small variations in pigment size can significantly impact light scattering and color appearance. Understanding the scattering and absorption properties of pigments across different wavelengths enables more precise prediction of the final color outcome (Berns, 2019) (Tabatabaei, 2019) .

1.4.2 Translucency and Opacity in Composite Restorations

Resin composites are semi-transparent materials capable of reflecting the colors of adjacent tooth tissues, materials, and backgrounds, resulting in perceptible color shifts between these structures. The interaction where aesthetic restorative materials assimilate the colors of nearby tooth structures is commonly referred to as the "chameleon effect" in dental literature. This effect is attributed to the reflected light and the inherent color of the adjacent tooth structures (Durand, 2021).

Translucency in resin composites is typically assessed using parameters like Translucency Parameter (TP) or Contrast Ratio (CR). It serves as an indicator of the material's ability to mask underlying colors or substrates effectively (Kim SJ, 2009). It has been shown that as the thickness of resin composite decreases, the TP value increases exponentially regardless of the color tone (Kamishima N, 2006;) (Kamishima N, 2005;) (Arimoto, 2010). The Contrast Ratio (CR) in modern resin composite materials, which is based on light reflection, is defined as the ratio of light reflected by a semi-transparent material against a black background to the light reflected under the same conditions against a white background. The thickness of the material significantly influences the Contrast Ratio and thereby affects translucency (JOHNSTON, 2014).

Composite materials exhibit varying degrees of translucency. Translucency refers to the property where part of the incident light on the material's surface passes through it, allowing visibility of the background. This characteristic is prominent in tooth enamel, which exhibits different levels of translucency. In contrast, opacity refers to the property where light cannot pass through the material's surface. Dentin, while not completely opaque, is more opaque compared to enamel. Enamel, although highly transparent, is not perfectly transparent. The degree of translucency is influenced by how deeply light penetrates into the tooth or restoration before being reflected outward (Carlos Rocha Gomes Torres, 2020).

Pigments added to resin composites can affect the color and diffusion of light; therefore, caution should be taken when including pigments in these materials to achieve optimal aesthetic results in clinical settings. The development of color using colored pigments is produced through the chemical energy exchange between light and pigments (S. Kalachandra, 1991).

Highly translucent composites that incorporate nanoparticles often enable the perception of the background color. The scattering of light within these materials is strongly influenced by the wavelength of the incident light and primarily determined by the size of the nanoparticles dispersed within the composite (Lee., 2007) . Different aesthetic restorative resin systems exhibit varying color and translucency effects, which are crucial considerations when choosing a restorative material (Pecho, 2016).

Translucency is a material property that permits light to pass through but scatters it, preventing clear visibility of objects behind the material. It can be described as an intermediate state between complete opacity and transparency. The translucency of dental resin composites is influenced by factors such as the scattering and absorption coefficients of the resin, filler particles, pigments, and opacifiers, which are also influenced by the material's thickness (JM, 2006,) (PÉREZ, 2010).

1.4.3 Opalescence in Composite

Composite resins should ideally exhibit opalescence to mimic the natural opalescence of dental enamel. The opalescence of aesthetic restorative materials is typically quantified using the opalescence parameter (OP). Unlike the translucency parameter (TP), which assesses the material's ability to mask underlying colors, OP evaluates the material's ability to reflect or refract light in a way that enhances its aesthetic appearance, often by adding depth and vitality to the restoration (Arimoto, 2010) .

This optical phenomenon known as opalescence varies depending on the brand and color of the resin-based composites used in dental restorations. Different composite materials may exhibit varying levels of opalescence due to differences in their formulation, including the types and sizes of filler particles, pigments, and additives used by different manufacturers (Bona, 2020).

1.4.4 Fluorescence in Composite Resins

Composite resins often incorporate fluorescent properties through the use of luminescent substances known as fluorophores. These substances can include rare earth elements such as europium, cerium, and ytterbium oxides, which are strategically employed to mimic the fluorescence found in natural dental structures. Elements from groups III, IV, and V of the periodic table are typically utilized to achieve this effect. It's important to note that the degree of fluorescence exhibited by composite materials can vary significantly depending on the specific formulation used. Historically, uranium oxide was also employed as a fluorescent material in dental composites. However, its use was discontinued due to concerns over radiation emission (Gamborena, 2011).

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CHAPTER IV

An Overview of Color in Dentistry

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Introduction

In today's dentistry, the concept of aesthetics is at the forefront for both patients and dentists. In restorative dentistry, it is very important to restore defective or missing tooth structure in order

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to ensure function and harmony with the oral tissues. In addition, tooth-restoration color matching has become an important factor due to increasing aesthetic expectations. (Abdulsamee & Nagi, 2020)

Aesthetics, which enable the creation of natural tooth-like restorations, consist of elements such as the shape, surface texture, and color of the restoration. In considering the properties of light, such as reflection and absorption, the most challenging aspect is selecting the color shade. (Özat, Tuncel & Eroğlu, 2013) Prior to selecting the most appropriate shade, it is essential to possess a comprehensive understanding of the fundamental principles of color and light, as well as the optical properties of the tooth and materials. This is crucial for the creation of highly natural-looking restorations. (Sikri, 2010) The concept of art within dentistry is particularly evident in this context.

Color Concept

Aesthetic appearance is influenced by a number of factors, including color, translucency, brightness, fluorescence, and opalescence. (Joiner, 2004) All of these factors are influenced by the interaction of a light source, an object, and an observer, such as a dentist or a patient. The existence of this triadic interaction is also necessary for the perception of color. When a light source interacts with an object, a portion of the light is absorbed by the object, while the reflected portion reaches the retina of the eye. Color is perceived as a consequence of this event. (Berns, 2019) The absorption and reflection of light result in variations in perception, which in turn give rise to the appearance of color shade. (Sengez & Dörter, 2019) In the absence of light, color does not exist. The human eye is sensitive to light with wavelengths between approximately 400 nm and 700 nm. The light between these wavelengths is also referred to as the visible light spectrum. (Abdulsamee & Nagi, 2020)

The results of the research indicate that the human brain is capable of distinguishing nearly one million color shades, with only 1% of these shades being visible to the human eye. It has been posited that electronic devices are capable of perceiving 10 million distinct color shades and classifying approximately 100,000 shades. (Jouhar, Ahmed & Khurshid, 2022)

Translucency

It can be defined as a transition between transparency and opacity. Enamel, translucent resin composites, and porcelains permit some of the incident light to pass through and reflect the remainder, thereby exhibiting translucent properties. (Jm, 2006) The process of demineralization in the enamel alters the reflection of the enamel and results in discoloration. Resin infiltration is one of the treatment methods used for this purpose. (Puleio & et al., 2021) Dentin and opaque porcelains that do not permit light to pass through exhibit an opaque character.(Jm, 2006)

Fluorescence

Fluorescence is defined as the emission of light at a longer wavelength while a substance absorbs light at a certain wavelength. Dentin exhibits greater fluorescence due to its higher organic concentration in comparison to enamel. This phenomenon is particularly attributable to the presence of amino acids, such as tryptophan, within the collagen structure. The fluorescence property confers brightness upon the material. (Abdulsamee & Nagi, 2020; Rajan & et al., 2020)

Opalescence

An optical property whereby a material appears to exhibit a different color when observed under transmitted light and reflected light. (Rajan & et al., 2020) The opalescence of enamel makes it appear yellowish or brownish under transmitted light and more bluish under reflected light. This characteristic of enamel gives it vitality and depth. The incisal halo, observed as a blue band especially near the incisal edge of the central teeth, is an opalescence reflection line. Light reaching the dentin from the enamel is reflected back to produce a counter opalescence effect, which gives the enamel a more orange color, especially in the mamelon region. (Abdulsamee & Nagi, 2020)

Metamerism

The fact that the color of the material appears different under different lighting conditions, such as daylight and fluorescent lamps is defined as metamerism. (Manappallil, 2015; Sengez & Dörter, 2019) Tooth and material color may give compatible results in one lighting condition and incompatible results in another lighting condition. When matching tooth and material color, it is also recommended to choose a lighting condition suitable for the place where the patient will spend more time. (Sakaguchi & Powers, 2012)

Surface Brightness

This optical property affects the appearance of teeth. In the case of polished and smooth surfaces, the angles of incident and reflected light are equal to each other, which results in a brighter surface structure. In the case of rougher surfaces, the light incident upon them is scattered, resulting in a reduction in surface brightness. (Alnusayri & et al., 2022; Sengez & Dörter, 2019)

Color Systems

While the color of teeth can be affected by many internal and external factors, the perception of color also varies depending on the individual and many other factors mentioned above. Different color systems have been developed to avoid confusion and to describe colors correctly. (Şeker & Sarı, 2019) While the CIELab color system is the most widely used system in dentistry, the CIEDE2000 color system is currently the preferred system due to its enhanced features.

Munsell Color System

The color system was devised by Alfred H. Munsell in 1898. The system is based on three parameters: hue, value, and chroma. (Berns, 2019)

Hue is defined as the shade of color. It is expressed as the dominant wavelength range in the visible light spectrum. (Fondriest, 2003) According to the Munsell color system, the hue is drawn on a circle (Figure 1.).(Abdulsamee & Nagi, 2020)

Value is the amount of light reflected from the surface of a material. (Fondriest, 2003) It refers to the darkness and lightness of the shade. It is the most important factor in determining the harmony between the restorative material and the tooth shade. It forms the vertical axis of the Munsell shade system and is defined as a gray scale from white to black (Figure 1.).(Abdulsamee & Nagi, 2020)

Chroma refers to the intensity and saturation of color. It forms the radial axis of the Munsell color system (Figure 1.). It is inversely proportional to value.(Abdulsamee & Nagi, 2020)

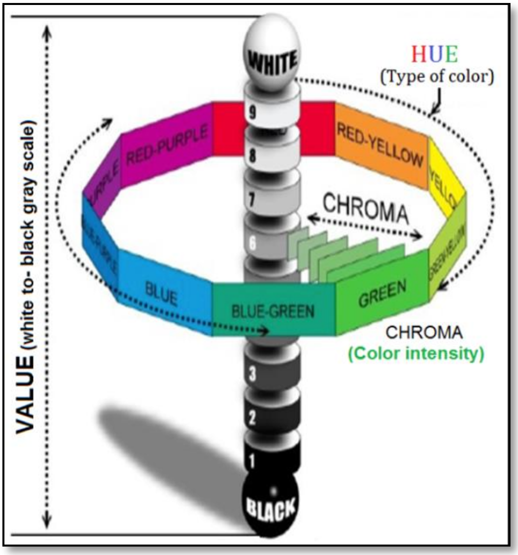

Figure 1. Munsell color system (Abdulsamee & Nagi, 2020)

CIE XYZ Color System

It is the color system developed by the Commission International de l'Éclairage (CIE) in 1931. It is one of the first standard color systems to be based on direct measurements of how the eye perceives color. It is based on the theory that the eye has receptors that can detect three primary colors (red, green, blue), while other colors are mixtures of these three primary colors. X, Y, Z values are calculated using the three primary color matching functions: red, green and blue. (Ragain, 2016)

CIELab Color System

The color measurement system, developed in 1976, is one of the most popular and widely used in the field. It is also known as the L^*, a^*, b^* color space. (Ragain, 2016)

L^* indicates lightness values that range from 0 to 100 from black to white, while a^* and b^* indicate chromaticity coordinates on the red-green axis and the blue-yellow axis. +a indicates the red, -a indicates the green color range, while +b indicates the yellow, -b indicates the blue color range (Figure 2.). (Sakaguchi & Powers, 2012)

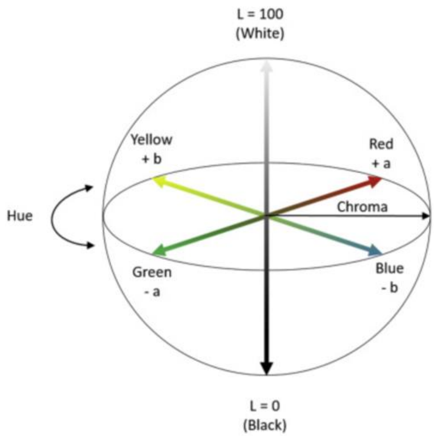

Figure 2. *The CIELab color space diagram*

(Ly, Dyer, Feig, Chien, & Del Bino, 2020)

The CIELab-based color difference (ΔE^*_{ab}) is calculated using the following formula:

$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ (Lee, 2005)

CIEDE2000 Color System

It is the most up-to-date color system that supports the development of the concepts in the Munsell color system. It is based on the CIELab color system and was developed to complement its shortcomings. In this color system, all changes are evaluated in the same proportion and the results can be determined more in accordance with the color difference values that the eye can perceive. (Fidan & Dereli, 2021; Ghinea & et al., 2010)

The CIEDE2000-based color difference (ΔE_{00}) is calculated using the following formula:

$$\Delta E_{00} = [(\frac{\Delta L'}{K_L S_L})^2 + (\frac{\Delta C'}{K_C S_C})^2 + (\frac{\Delta H'}{K_H S_H})^2 + R_T(\frac{\Delta C'}{K_C S_C})(\frac{\Delta H'}{K_H S_H})]^{1/2}$$

(Gregor & et al., 2016)

Color Measurement Methods

- Evaluation of color matching between tooth and restorative material
- Evaluation of the results obtained with bleaching
- Evaluation of color stability of restorative materials in in vitro studies
- Evaluation of clinically detectable and acceptable color change thresholds

such as, color measurement methods can be used in many studies related to restorative dentistry. (Şeker & Sarı, 2019)

Color measurements can be made using visual or instrumental methods. It is very important to make fast and reproducible measurements when making measurements. (Müdüroğlu, Kıvrak & Nalçacı, 2018)

Visual Color Measurement Method

The visual approach is the most preferred color measurement method clinically. In this approach, the color of the restorative material is selected by subjectively comparing it to the color scale of the tooth. However, this approach may result in erroneous results due to the subjective nature of the comparison. The visual approach is not without limitations. These include age, eye disorder, fatigue, emotional state, clinical experience in color selection, and the lighting conditions of the environment in which the color is selected. There is even a belief by many researchers that women make better color selection than men. Despite all these, the visual method is widely preferred because it requires less technological knowledge and is less costly. (Aswini & et al., 2019)

The color scales used in the visual measurement method are resin composite, acrylic or ceramic based and contain natural shades suitable for tooth structures. (Jouhar & et al., 2022)

VITA Classical (VITA Zahnfabrik, Bad Sackingen, Germany), VITA Toothguide 3D-Master shade guide (VITA Zahnfabrik, Bad Sackingen, Germany) and Chromascop (Ivoclar Vivadent, Buffalo, USA) are currently used in dentistry. These color scales are based on the Munsell color system. (Jouhar & et al., 2022)

In the VITA Classical color scale, hue is represented by the letters A, B, C, and D, with each letter comprising four subdivisions. As the numerical value increases, chroma increases and value decreases (Figure 3.). (Jouhar & et al., 2022)

Figure 3. *VITA Classical Shade Guide (Sengez & Dörter, 2019)*

VITA Toothguide 3-D Master has been improved compared to Vita Classical. The shade guide is based on Value and has 26 shades (Figure 4.). One of its advantages is that it has a wide range of colors and adapts better to natural teeth. (Jouhar & et al., 2022; Sengez & Dörter, 2019)

Figure 4. *VITA Toothguide 3-D Master Shade Guide (Albert & et al., 2019; Sengez & Dörter, 2019)*

In Chromascop, numbers are used to identify shades of color (100 = white, 200 = yellow, 300 = orange, 400 = gray, 500 = brown) (Figure 5.). Within groups, the numbers 10, 20, 30, 40 represent chroma. (Jouhar & et al., 2022)

Figure 5. *Chromascop Shade Guide (Jouhar & et al., 2022)*

Instrumental Color Measurement Methods

Although the disadvantages of instrumental color measurement methods are that they are more costly and not easily accessible compared to the visual method, their use is increasing in today's dentistry. Spectrophotometers, colorimeters, and digital cameras are among the instruments used for color selection. These devices are preferred for daily clinical use as well as for in vivo or in vitro research. In the measurements, the color parameters of the CIELab color system are obtained and allow numerical calculation of color values. Objective results are obtained and measurements can be repeated quickly. (Sengez & Dörter, 2019)

Spectrophotometers are sensitive, convenient, and flexible instruments that can be used for the selection and matching of colors. The instrument contains a prism that separates white light into a spectrum of 10-20 nm wavelengths, in addition to a multitude of sensors. The device is capable of distinguishing colors that the human eye cannot detect due to its use of sensors that can measure at different wavelengths. (Müdüroğlu, Kıvrak & Nalçacı, 2018) The studies show that spectrophotometers can be used to distinguish metamerism and give more reliable and clearer results than calorimeters. (Chu, 2004; Kim-Pusateri & et al., 2009) In comparison to the visual method, spectrophotometers provided a more objective match in 93.3% of cases. In addition, there are also researchers who state that it is more valuable to use it in combination with the visual method. (Paul & et al., 2002) Examples of spectrophotometers used include Shade-X (X-Rite Grandville, MI, USA), SpectroShade Micro (MHT, Niederhasli, Switzerland), and VITA Easyshade (VITA Zahnfabrik, Bad Sackingen, Germany). (Şeker & Sarı, 2019) The VITA Easyshade V is shown in Figure 6.

Figure 6. *VITA Easyshade V*

Colorimeters are digital measuring devices that quantify the color coordinate values of X, Y, and Z by filtering the light reflected from the material as red, green, and blue, that is, they have 3 sensors in their structure. It is a small and easy-to-use device, but the short lifetime of the filters and the need for replacement are disadvantages in terms of both measurement accuracy and long-term use. This device is recommended for flat surface measurements. (Kim-Pusateri & et al., 2009) However, since teeth generally do not have flat surfaces, it can give erroneous results on the teeth. Examples of colorimeters include Shade Vision (X-Rite, Grandville, MI, USA), Cynovad Shade Scan (Cynovad, Montreal, Canada), Shade Eye (Shofu, Ratingen, Germany) (Figure 7.), Minolta CR-321 (Konica Minolta, Tokyo, Japan), and Identa Color II (Identa, Holback, Denmark). (Şeker & Sarı, 2019)

Figure 7. *Shofu ShadeEye (Ragain, 2016)*

Spectroradiometers are color measurement devices that are mainly produced to determine brightness with radiometric measurements, which are preferred for dental use due to the translucent structure of teeth and restorative materials. Spectroradiometers differ from spectrophotometers in that their light sources are not fixed and they can perform non-contact measurements. Translucency and surface abnormalities of the teeth may be the reason why this device is preferred for color measurements. (Şeker & Sarı, 2019)

The digital camera and imaging systems are based on the principle of taking an image of the tooth or material with a digital camera and measuring the L*, a*, and b* values on a computer that is connected to the camera. (Wee & et al., 2006) Additionally, they may be referred to as RGB devices. Although digital imaging systems are very popular today, image quality is very important for color measurement. The most important advantages of these systems are obtaining the color of the material or the tooth as a whole, non-contact measurement, and recording the measurements by creating a database. Studies on spectrophotometer and digital image methods have shown reliable results in tooth color measurements. (Şeker & Sarı, 2019)

Hybrid instruments are a combination of spectrophotometric examination and digital imaging. SpectroShade is an example of a hybrid instrument (Figure 8.). SpectroShade was developed for use with digital cameras and Windows computers. It uses the ClearMatch software system (Hood River, OR, USA: Smart Technology). (Jouhar & et al., 2022)

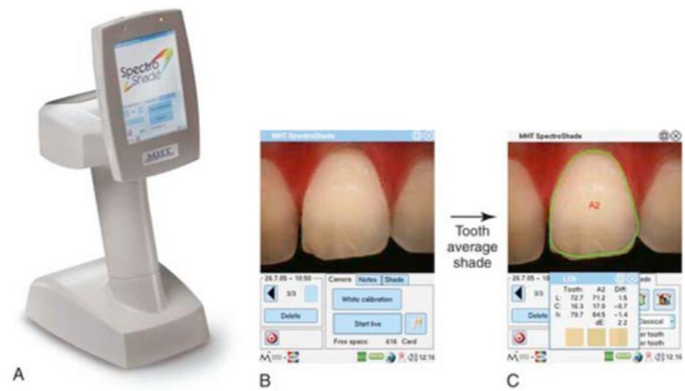

Figure 8. *A) SpektroShade B-C) Numerical comparison of color parameters of natural tooth and selected color (Abdulsamee & Nagi, 2020)*

In addition to these systems, intraoral scanners can also be used for color selection with the software they have included in recent years. By capturing color images, they can accurately distinguish between hard and soft tissue. The 3Shape Trios (3Shape, Copenhagen, Denmark) uses photo imaging for scanning, while scanners such as Omnicam and Primescan (Denstply Sirona, Bensheim, Germany) use video imaging techniques. (Ebeid, Sabet & Della Bona, 2021) A study comparing the color selection accuracy of the 3Shape Trios and colorimetry concluded that the 3Shape Trios did not achieve satisfactory success. (Yoon & et al., 2018) In other studies that compared the color measurement accuracy of Vita Easyshade and 3Shape Trios, no significant difference was found between the two. It was thus determined that the intraoral scanner exhibited comparable accuracy to a spectrophotometer in clinical conditions. (Liberato & et al., 2019; Ebeid, Sabet & Della Bona, 2021) Although not statistically different, Omnicam showed the lowest accuracy among the scanners. This has been attributed in the literature to the lower scanning sensitivity of the device. (Ebeid, Sabet & Della Bona, 2021) In the study comparing visual color measurement with 3Shape Trios in terms of color determination, no significant difference was found between the two methods in terms of accuracy and repeatability. (Moussaoui & et al., 2018) Future studies should investigate the potential for new intraoral scanners to replace visual methods in color selection. (Abu-Hossin & et al., 2023)

Color Selection in the Clinic

The choice of tooth and material color is very important in restorative dentistry. For an appropriate and correct selection, value should be chosen first, followed by chroma and hue respectively. (Jouhar & et al., 2022)

A clinically acceptable color match can be achieved by reducing the influence of subjective errors in visual color selection and improving the clinical conditions. A number of factors can influence the selection of colors.

Lighting:

Midday sunlight is considered ideal for color selection. Between 10.00 and 14.00 the color temperature is 5500 K, which is shown to cause accurate color matching. (Borse & Chaware, 2020) In clinics that cannot receive daylight, artificial lighting methods are considered clinically appropriate, although they cannot fully replace daylight. (Jouhar & et al., 2022)

Environment:

Brightly colored environment, clothing, accessories such as jewelry may affect the reflected light and cause negativity in color selection. In addition, the patient's lipstick should be removed before color selection, as it may cause negativity in color perception. A very light gray background is the ideal environment for color selection. (Jouhar & et al., 2022)

Teeth:

It is important that the teeth to be selected for color selection are cleaned from plaque and tartar and form a clean surface. Given that anatomical differences in the teeth may result in light reflection in varying directions and at different wavelengths, it is advisable to conduct color assessment at different angles. (Borse & Chaware, 2020) Dehydrated teeth appear whiter. It is recommended to choose the color without leaving the patient's mouth open for a long time, without using rubber dam and without any preparation on the teeth. In bleached teeth, color control should not be done immediately due to dehydration caused by the bleaching process. A color comparison can be made in approximately two to three weeks. (Jouhar & et al., 2022)

Patient Position:

To ensure optimal vision and comfort, the patient's teeth and the dentist's eye level should be aligned. The distance between the oral cavity and the dentist should be between 61-183 cm. (Jouhar & et al., 2022)

Timing:

Hours when the dentist does not have eye strain should be preferred. Decisions made in the first 5-7 seconds are usually the most accurate choices in color harmony. (Kahramanoğlu & Özkan, 2013) When the eye becomes fatigued, it can be rested by focusing on blue-gray tones. (Sengez & Dörter, 2019)

Other Factors Affecting Color Selection:

- Achieving color harmony also varies according to the knowledge, experience and experience of the physician. The tendency to see yellow-brown increases with aging. This situation starts in the 30s and becomes more pronounced in the 50s.
- It is generally stated that women are more successful than men in color discrimination.
- In cases of visual impairment, such as achromatism, dichromatism and trichromatism, errors in color perception may occur.
- Differences in visual perception between the right and left eye may also result in failure.
- The fatigue of the dentist who will make color selection during the day also negatively affects the color harmony. Especially the appointments of long-lasting procedures or cases requiring color selection

on the same day may cause this situation. (Jouhar & et al., 2022)

Color Stability of Restorative Materials

Color stability is defined as the preservation of the original color of the material without any change. Color stability can be affected by many factors such as the mechanical and physical properties of the material and the oral environment. Inorganic filler particle size, resin matrix structure, polymerization depth and surface quality of composite resins are examples of these factors. (Ashok & Jayalakshmi, 2017)

In the oral environment, restorations are constantly exposed to saliva, eating and drinking activity, smoking, brushing and temperature changes. (Ashok & Jayalakshmi, 2017) Due to these situations, the characteristic of the restorations deteriorates over time and patients become aesthetically uncomfortable. Thus, existing restorations may need to be corrected or replaced. Unacceptable color matching is one of the main reasons for restoration replacement. Long-term clinical studies have also shown that restoration discoloration can cause significant problems.

The color stability of restorative materials is also investigated under in vitro conditions using different materials and aging methods. These methods include immersion in different solutions, brushing, and thermal cycling.

In the literature, samples prepared from restorative materials in in vitro studies are usually disk-shaped and 2 mm thick. (Paolone & et al., 2022) There is no consensus on the effect of finishing and polishing on the color stability of the surfaces of these samples.

Some authors have reported that unpolished surfaces will cause more discoloration than polished surfaces (De Souza, & et al., 2013; Yildiz & et al., 2015), while others have reported that polished surfaces may not be resistant to discoloration (Patel & et al., 2004). There is literature showing that by re-polishing colored samples, the external discoloration can be reduced or completely removed, thereby restoring the color. Re-polishing is an additional step recommended in such studies. (Paolone & et al., 2022)

Brushing simulation is not widely used in color stability studies. However, it is reported in the literature that pigments deposited on the sample surface can be removed from the surface by brushing. (Bezgin & et al., 2015; Paolone & et al., 2022)

When the literature is reviewed, the most preferred solutions in color stability studies are coffee, tea, red wine, and cola. These cause external coloration in materials. Although the retention time in these solutions varies, a 7-day retention time is generally preferred. (Paolone & et al., 2022)

Spectrophotometers are widely used for color changes, but other measuring instruments are also used. Although the CIELab color system is more widely preferred for color change calculations, CIEDE2000 is the most popular and current color system. (Paolone & et al., 2022)

Results

Due to the increasing aesthetic demands on patients, it is necessary to first understand the concept of color and the principles of light in order to make a highly natural restoration. In addition to the visual color measurement method, the mastery of other measurement methods helps to prevent negative situations that may occur in the clinic. In a world moving towards digitalization, the combination of digital and visual methods makes it possible to obtain accurate and reliable results. In vitro studies of color stability can be used to simulate the clinical situation by evaluating material properties and factors that can cause external discoloration. The results of these studies can be applied in the clinic and potentially lead to more successful restorations.

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