CHAPTER 2

LITERATURE REVIEW

2.1 Edentulism

The governing body of health sector worldwide has implemented several measures, including the formulation, adoption, and implementation of plans and policies, to address the healthcare needs of the elderly, including their oral health (Douglass et al., 2002). However, despite these initiatives, oral disease remains a significant public health issue globally, particularly among older adults.

In Malaysia, as in many countries, the ageing population is growing, leading to an increased focus on elderly healthcare. The government recognizes the importance of addressing the specific health needs of older adults, including oral health, to ensure a better quality of life for this demographic. According to the Ministry of Health (MOH) Malaysia, many edentulous older adults struggle with significant impacts on their quality of life due to tooth loss. As part of their efforts, Malaysia's government has developed strategic plans and policies to promote preventive dental care, provide dental services, encourage greater use of preventive care, and improve oral health education among the elderly population (NOHSA, 2011).

Despite these efforts, oral disease remains a significant challenge worldwide, particularly among older adults. Factors such as a lack of awareness, limited access to dental care, and financial constraints can contribute to oral health issues in this age group (Mitchell et al., 2013). Additionally, as people age, they may be more susceptible to some dental issues, such as tooth decay, gum disease, and tooth loss (Al-Rafee, 2020). These oral diseases and their sequels will cause pain and discomfort resulting in impairment of function and reduced quality of life. Dental caries and periodontal diseases are the main causative factors in teeth loss and eventually, if untreated, lead to edentulism (Jaafar et al., 2014).

Edentulism is the state of being edentulous, or without natural teeth. Complete edentulism is an oral cavity without any teeth. Patients suffering from edentulism exhibit a wide range of physical variations and health conditions. Tooth loss can affect mastication, speech, and aesthetics which in turn reduces the quality of life (Al-Rafee, 2020). Comprehensive and integrated healthcare approaches are needed to combat oral disease among older adults. This includes strengthening geriatric dental services, improving collaboration between dental and medical professionals, and implementing preventive measures on a broader scale (Oberoi et al., 2018).

2.2 Dental Prostheses

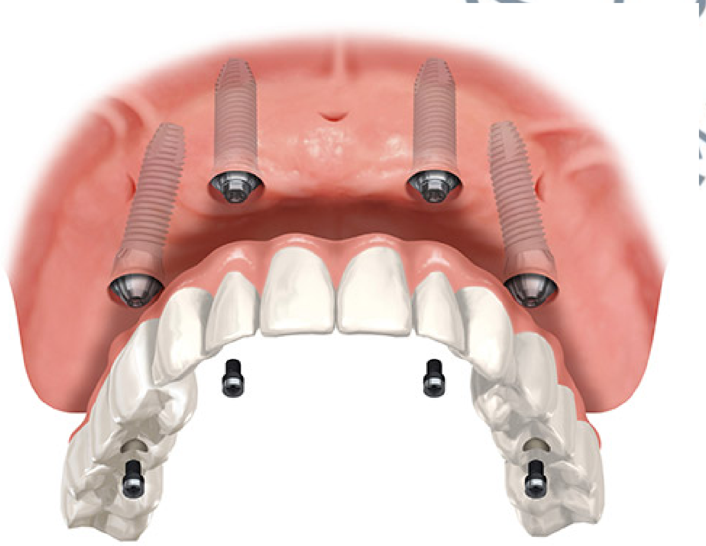
Dental prostheses are indispensable in addressing the challenges posed by tooth loss. One of their primary functions is the restoration of chewing functionality, crucial for proper digestion and overall health. Additionally, they play a pivotal role in preserving facial structure (Pun et al., 2011). When teeth are lost, the jawbone can deteriorate, leading to a sunken facial appearance (Alhallak et al., 2023).

Moreover, speech can be significantly affected by missing teeth, particularly in the front. Dental prostheses can aid in proper articulation, enabling individuals to speak clearly and confidently (Miyaura et al., 2000). Furthermore, they offer a profound aesthetic improvement. Artificial teeth are fabricated to resemble natural teeth, this kind of dental prosthesis can restore a complete smile, positively impacting self-image, and improving social interactions. Importantly, they prevent neighbouring teeth from shifting into empty spaces, averting misalignment, and potential further tooth loss (Pun et al., 2011; Tian et al., 2021).

Besides the physical aspects, dental prostheses have proved to boost confidence and overall quality of life (Salernitano & Migliaresi, 2003). Missing teeth can lead to withdrawal from social activities, and prostheses provide the assurance to smile, eat, and speak without reservation (Zitzmann et al., 2007). They also contribute to better oral hygiene practices by distributing chewing forces evenly, reducing the risk of damage to remaining teeth. Dental prostheses are available in a wide range of options, including full and partial dentures, bridges, crowns, and implants. These dental prostheses can be tailored to suit each individual's unique needs and preferences. In essence, they are fundamental in modern dentistry, not only for restoring oral function and aesthetics but also for enhancing overall well-being (Miyaura et al., 2000).

2.2.1 Dental Implant

Dental implants are considered one of the best options for replacing missing teeth. This procedure involves the surgical placement of a titanium post into the jawbone, effectively acting as a synthetic tooth root. This post provides a sturdy foundation for attaching a crown, bridge, or denture (Avetisyan et al., 2021). One of the standout advantages of implants is their remarkable stability and longevity (Hidalgo et al., 2021). They not only look and feel like natural teeth but also function in the same way. Additionally, they help prevent the deterioration of the jawbone, which can occur after tooth loss. However, it's important to note that the implantation process is a surgical procedure, which may require a period of healing before the final restoration can be attached (Ercoli & Caton, 2018). Moreover, like any surgical procedure, dental implants come with a degree of treatment morbidity. This refers to the discomfort, complications, and potential risks associated with the surgical placement of dental implants. For instance, patients with certain medical conditions, such as uncontrolled diabetes or autoimmune disorders, may have a higher risk of complications during the implant procedure (Afzal, 2014). Additionally, while highly effective, implants can be more expensive than other tooth replacement options.



Source: Retrieved from https://bexleydental.com.au/dental-implants/what-is-all-on-4/

Figure 2.1: All on four dental implant technique

2.2.2 Dental Bridge

Dental bridge is another reliable option for replacing one or more missing teeth. This restoration consists of two main components: the artificial teeth, known as pontics, and the supporting crowns, which are affixed to the adjacent natural teeth or dental implants (W. Li et al., 2004). Similar to the dental crown, the process of getting a dental bridge involved removal of a portion of enamel and dentine to make room for the bridge that will be placed over them. Dental bridges have several advantages, including effectively restoring the ability to chew and speak properly, maintain facial structure, and distribute bite forces evenly. Additionally, they also prevent adjacent teeth from shifting out of position (Studart et al., 2007). From an aesthetic perspective, bridges provide a natural appearance, blending seamlessly with the existing teeth.

Dental bridge can be composed of various materials, including metals like gold or alloys, porcelain-fused-to-metal (PFM), or all-ceramic, ensuring durability and a natural aesthetic appeal. However, the dental bridge comes with some limitations. For instance, the abutment teeth need to be strong and healthy enough to support the bridge, and high amount of tooth structure including enamel and dentine has to be removed, which can make them more susceptible to dental issues in the future such as loss of pulp vitality (Alharby et al., 2018). Additionally, like all dental restorations, bridges may require replacement or maintenance over time due to wear and tear.

Source: Retrieved from https://www.lighthousedentalcentre.com/blog/9-things-to-know-about-dental-bridges

Figure 2.2: Dental bridge

2.2.3 Removable Denture

Dentures are dental prostheses designed to replace missing teeth and surrounding oral tissues, making them a suitable and effective solution for individuals suffering from partial or complete edentulism. Dentures come in two primary types: partial dentures and complete dentures. Partial dentures are used when some natural teeth remain in the mouth, while complete dentures are employed when all natural teeth are missing. Both types of dentures are custom-made to fit the patient's mouth, providing a natural-looking and comfortable solution to restore oral function and aesthetics. Additionally, the denture base provides stability and retention for the denture by supporting the artificial teeth. As a result, it absorbs the functional forces generated during occlusion and efficiently transmits these forces to the surrounding oral structures that provide support (Kewekordes et al., 2018).

Dentures aim to facilitate proper chewing, enabling individuals to break down food efficiently for digestion, and they help improve speech clarity by providing support to the tongue and lips (Wang et al., 2021). Moreover, dentures offer aesthetic benefits, custom-made to fit the patient's mouth and facial features, restoring a natural-looking smile and facial structure, which can significantly boost self-esteem and social interactions. Beyond aesthetics, dentures also provide facial support, preventing facial changes associated with tooth loss, such as sagging cheeks and sunken lips (Singh et al., 2014). Furthermore, dentures are a cost-effective tooth replacement option, more affordable than alternatives like dental implants, making them accessible to a broader range of patients (Mohd Farid et al., 2022). In addition, these dentures can be promptly fabricated, allowing edentulous individuals to regain their oral function and aesthetics in a brief period (Akl & Stendahl, 2022).

As dentures reside in direct contact with oral tissues, it is essential to prioritize biocompatibility. Biocompatible denture materials are carefully chosen to ensure they do not cause irritation, inflammation, or adverse reactions in the surrounding oral cells and tissues (Vyas et al., 2022). This aspect is vital to ensure the patient's comfort, overall oral health, and long-term acceptance of the denture. Furthermore, it's crucial to consider the fungal adherence and antibacterial activity as essential properties in dentures to prevent denture stomatitis. Denture stomatitis, also known as denture-related erythematous candidiasis, is a common condition among denture wearers. It's characterized by inflammation and redness of the oral mucosa, particularly the palatal area covered by the upper denture. The primary cause of denture stomatitis is an overgrowth of Candida species, particularly *Candida albicans*, which are naturally occurring fungi in the oral cavity (Hirasawa et al., 2018). Ability to reduce the fungal adhesion on the denture surface or inhibiting the growth of the *C. albicans* can prevent denture stomatitis among denture wearers (Meirowitz et al., 2021).

Moreover, dentures must possess exceptional mechanical strength to withstand the complex forces they encounter during daily functional movement in mastication, which exert stress on the denture (Derban et al., 2021). The combined attributes of biocompatibility and mechanical strength form the foundation for successful denture design. By ensuring that the denture is well-tolerated by the oral tissues and can withstand the forces it encounters daily, the prosthesis achieves stability, retention, and functionality. A well-fabricated denture significantly impacts the patient's oral function, speech, aesthetics, and overall quality of life, promoting confidence and facilitating proper nutrition without bringing any adverse effects. Hence, an appropriate denture material is of the utmost importance to achieve these objectives.

Source: Retrieved from https://aestheticdentalclinic.com.au/living-with-removable-partial-dentures-lifestyle-tips-and-adjustments/

Figure 2.3: Removable partial and complete denture

2.2.4 Denture Base Material

Introduced in the 1930s, methacrylate base resin quickly gained popularity in the dental field due to its favourable attributes, including sufficient mechanical strength, biocompatibility, ease of production, and cost-effectiveness (Gautam et al., 2012; Hada et al., 2021). As a result of these advantages, Polymethyl Methacrylate (PMMA) emerged as the most widely utilized material for fabricating denture bases since its inception in 1936 (Iwaki et al., 2020). Its acquired properties have allowed it to entirely replace previously used denture base materials such as porcelain, vulcanite, aluminium, and many more (Johnson WW, 1959; Murray & Darvell, 1993; Khindria et al., 2009).

Furthermore, PMMA has garnered significant attention within the medical industries, particularly in the creation of prostheses for orthopaedic, maxillofacial, and cranioplasty applications (Zafar, 2020). Its versatility and biocompatibility have made it a preferred choice for crafting prosthetic solutions that enhance patients' quality of life. However, the remarkable utility of PMMA is accompanied by certain inherent limitations that have somewhat restrained its broader clinical use. One major drawback of methacrylic resin from which PMMA is derived tends to undergo high-volume shrinkage during the polymerization process (Hada et al., 2022).

Polymerization is a process that involves the conversion of methyl methacrylate (MMA) monomers into polymers, eventually forming the PMMA structure. This shrinkage can potentially compromise the accuracy of the final prosthesis, leading to fit issues or discomfort for the patient. Therefore, researchers and dental professionals have worked to address the limitations of PMMA and explore alternative materials. Consequently, a variety of resin monomers have been synthesized and introduced over the years to cater the diverse dental applications (Sideridou et al., 2002). These materials offer unique attributes that aim to enhance the performance and versatility of dental prostheses (Barszczewska-Rybarek & Jurczyk, 2015).

Among these alternatives are Bisphenol A-Glycidyl methacrylate (Bis-GMA), Ethoxylated Bisphenol A Glycol Dimethacrylate (Bis-EMA), Triethylene Glycol Dimethacrylate (TEGDMA), and Urethane Dimethacrylate (UDMA) (Moharram et al., 1992; Durner et al., 2015). Each of these monomers is a member of the dimethacrylate family and presents specific advantages suited to various clinical scenarios. For instance, Bis-GMA is recognized for its remarkable mechanical properties and durability, making it suitable for dental composites and adhesives. However, it is associated with a comparatively higher degree of polymerization shrinkage, potentially leading to challenges in achieving precise fitting (Barszczewska-Rybarek & Jurczyk, 2015).

On the other hand, Bis-EMA presents a compelling solution by mitigating the concern of shrinkage. Its advantages include low water sorption, low viscosity, low shrinkage during polymerization, and adequate mechanical strength. These characteristics enhance marginal integrity while introducing improved flexibility to the material (Pratap et al., 2019). Its unique attributes are ideal for applications where minimizing shrinkage and enhancing adaptability are pivotal, making it a valuable component in various dental formulations (Durner et al., 2015).

In addition, TEGDMA offers a distinct advantage in its compatibility with other monomers. This feature enables versatile formulation options, allowing dental professionals to tailor materials to specific clinical needs. For instance, it has been frequently used as a diluent in the composites resin matrix that contains highly viscous monomers such as Bis-GMA and UDMA (Alshali et al., 2013). Nevertheless, there are some drawbacks by incorporating TEGDMA into the resin matrix, which are high water absorption and reduce mechanical strength, which can affect the long-term stability and durability of restorations (Lin et al., 2020).

Additionally, UDMA emerges as a monomer characterized by exceptional mechanical properties and biocompatibility. These qualities contribute to its preference for restorative materials that demand high strength and resilience, making it particularly suitable for posterior restorations and prostheses requiring enhanced durability (S. R. Kumar et al., 2016). Since UDMA has a significantly lower viscosity, higher mobility, and greater toughness than Bis-GMA, progressively took the place of Bis-GMA in numerous commercially accessible dental composite resins (Pratap et al., 2019).

2.3 Polymerization of Resin Matrix

The polymerization process initiates through the generation of a free radical, accomplished either chemically or through the application of external energy such as heat, light, or microwaves (Zafar, 2020). The conversion of monomers to polymers through polymerization can be categorized into three distinct phases which are namely initiation, propagation, and termination.

Initiation marks the inception of a cascade of reactions, propelling the polymerization forward. During this stage, a trigger (heat, light, or other form of energy) initiates the formation of free radicals or other active species. These radicals are highly reactive and possess unpaired electrons, rendering them eager to engage in chemical bonds with other molecules (M. Kumar et al., 2021). In the subsequent propagation stage, the reactive radicals formed during initiation start interacting with monomer molecules. The active radicals bind to the monomers, creating a new reactive site on the monomer itself. This, in turn, generates another radical that can react with additional monomers, leading to a chain reaction. The polymer chain gradually elongates as monomers continuously join the growing structure, creating a polymer structure (Corrigan et al., 2020).

Lastly, the termination phase is responsible for concluding the polymerization process. It involves the deactivation of the active radicals, halting the chain growth. This can occur through various mechanisms, including the recombination of radicals or the transfer of a radical to a species that has no further reactivity. The termination phase ensures that the polymerization reaches a controlled endpoint, preventing excessive chain growth and yielding a stable polymer structure (Sideridou et al., 2002).

These three phases of initiation, propagation, and termination collectively define the polymerization process. The sequence of events during each phase dictates the characteristics of the resulting polymer material. The rate of polymerization, the molecular weight of the polymer chains, and the overall structure of the material are influenced by the interplay between these phases (Moens et al., 2020).

2.3.1 Heat-Polymerized Resin

Heat-polymerized or heat-cure resins are commonly used to fabricate denture bases. Owning to the advantage of slow settling time, this type of material is particularly suitable for fabricating larger restorations or prostheses, allowing ample working time before the reaction sets in. To initiate the polymerization process that transforms monomers into polymers, a suitable combination of initiators, cross-linking agents, and inhibitors is introduced into the resin matrix (John et al., 2001). For instance, in the case of heat-curing PMMA, the formulation might encompass benzoyl peroxide as an initiator, ethylene glycol dimethacrylate as a cross-linking agent, dibutyl phthalate as a plasticizer, and hydroquinone as an inhibitor. The polymerization procedure initiates by blending PMMA powder with MMA liquid. Subsequently, the mixture is exposed to a heated water bath to activate the initiator. This initiation step triggers the gradual conversion of monomers into a polymer chain. Eventually, this process yields the desired PMMA structure.

Heat-polymerized resins exhibit a notably elevated degree of monomer conversion primarily attributed to their extended curing period, which often spans around 9 hours within a heated water bath (Choi et al., 2021). This protracted curing duration enables the attainment of a heightened degree of conversion; essentially, more monomers transform into polymer chains. This accomplishment, however, comes with the trade-off of a longer polymerization timeline. Yet, the extended process confers exceptional mechanical properties and commendable biocompatibility to the resulting material (Perea-Lowery et al., 2021b).

This enhanced monomer conversion translates to a denture material with improved strength, durability, and overall performance. The prolonged polymerization fosters comprehensive cross-linking and structural integrity within the polymer matrix (Krishna Alla et al., 2015). Moreover, the higher degree of conversion in heat-polymerized resins substantially diminishes the presence of residual monomers within the denture structure. This reduction in residual monomers is vital as it mitigates the potential leaching of these compounds, which could otherwise irritate the oral tissues of denture wearers (Rashid et al., 2015). The resulting denture offers not only impressive mechanical attributes but also a reduced risk of causing discomfort or adverse reactions to the patient's oral environment.

Nonetheless, the heat generated during polymerization can potentially cause distortion or warping, resulting in dimensional inaccuracy within the denture and ultimately affecting the comfortableness of the denture wearer. Therefore the polymerization process must necessitate careful regulation of temperature and curing time (Batisse & Nicolas, 2021).

2.3.2 Cold-Polymerized Resin

Cold-cured resin, often referred to as chemically cured or auto-polymerizing resin, possesses a unique composition and polymerization mechanism that distinguishes it from heat-cured resin. Unlike heat-cured resin, cold-cured resin operates independently of external thermal energy to initiate the polymerization process.

In cold-cured resin systems, the polymerization initiation is driven by a chemical activator, present within the material, which initiates the reaction without the need for elevated temperatures (So et al., 2012). This aspect brings about several distinctive features and benefits. Cold-cured resins are particularly suitable for situations where controlled heating is not feasible, such as chairside repairs or refurbishment of dentures. Moreover, their ability to polymerize at room temperature provides a practical advantage in situations where access to specialized curing equipment is limited. Additionally, the cold-curing process only requires a short curing time, facilitating swift procedures such as onsite denture repairs. Another notable advantage of cold-cured resin is its greater dimensional accuracy and flexibility (Frigione et al., 2020). Consequently, the polymerization shrinkage exhibited by cold-cured resin is notably lower than that observed in heat-cured resin materials (Shim et al., 2020).

However, the short curing time is associated with one major drawback, a low degree of polymerization. This reduced degree of polymerization can exert a substantial influence on both the mechanical and biological attributes of the cold-cured resin (So et al., 2012). The uncured monomers entrapped within the partially polymerized resin matrix possess the potential to leach out over time, potentially causing discomfort or irritation to denture wearers. Moreover, a lower degree of polymerization within the resin matrix imparts certain mechanical vulnerabilities (Rudawska & Frigione, 2021). Reduced polymerization translates to diminished strength and hardness, elevating the risk of mechanical failure under the forces exerted during mastication. Furthermore, reports have indicated issues with colour stability, where the material might be prone to discolouration over time (Zafar, 2020). Additionally, these resins may exhibit higher water sorption, leading to potential changes in the material's physical properties over extended periods (Perea-Lowery et al., 2021b).

Efforts have been made by incorporating filler particles such as zirconia (ZrO_2) and boron nitride into the cold-cured resin matrix (Alqahtani, 2020a). The addition of reinforcing particles has improved the overall mechanical properties of the cold-cured resin, particularly in terms of flexural strength and surface hardness (Alqahtani, 2020b). However, the reinforced cold-cured resin continues to face challenges in achieving a high degree of polymerization. Due to the notable abundance of residue monomers within the resin material, cold-cured resins are not considered as a primary option for long-term dental prosthetics (Krishna Alla et al., 2015).

2.3.3 Light-Polymerized Resin

Light-cured resin materials utilized the principle of photopolymerization, where a photo-sensitive agent, also known as a photo-initiator was added to the resin. This photo-initiator will be activated and initiate the polymerization process upon light irradiation, usually in the blue light spectrum. This initiation leads to rapid polymerization, offering exceptional control over the process (Hassan et al., 2019).

One of the primary benefits of light-cured resin materials is their ability to initiate polymerization on demand. Dental practitioners have direct control over the polymerization process, ensuring precise placement and curing of the material exactly when needed (Shim, Lee, et al., 2020). This is especially advantageous for procedures that require meticulous layering, sculpting, or adjustments. Furthermore, light-cured materials can cure rapidly under a curing light, significantly reducing the overall procedure time. This efficiency benefits both patients and dental professionals by minimizing chairside time and enhancing patient comfort (Shim, Lee, et al., 2020). Additionally, light-cured resin materials often exhibit less polymerization shrinkage compared to other polymerization methods. This is attributed to the fact that the polymerization process generates minimal heat, thereby reducing the likelihood of the cured material warping during the subsequent cooling phase (Ng et al., 2020). This property allows better adaptation of the material to the oral cavity walls, resulting in less stress on the restoration and reduced risk of marginal gaps.

However, there is one major drawback associated with the light-cured resin material, which is the limited curing depth, especially in deeper restorations (Sideridou et al., 2002). Since the penetration of light is limited, it can greatly affect the depth of cure in thicker or deeper restorations. Additionally, different curing lights have varying wavelengths and intensities. Inadequate light output or incorrect light-curing techniques can compromise the material's polymerization and further affect the mechanical and biological properties. Ergo, proper curing light selection and technique are crucial to ensure complete polymerization throughout the material. and proper light intensity and exposure time are crucial for ensuring complete polymerization (Moldovan et al., 2019).

In the realm of practical dentistry, the utilization of different resin materials represents a dynamic interplay between advantages and limitations, each tailored to distinct clinical scenarios. The heat-polymerized material has the highest overall strength among other types of resin due to its ability to achieve a higher degree of polymerization. However, polymerization shrinkage and long curing are the major drawbacks that hindered its profound usage. Conversely, light-cured resins stand out for their precision, enabling on-demand polymerization under controlled conditions, and reduced curing time enhances overall efficiency. In essence, the selection of a resin material hinges upon the clinical context, balancing the advantages and drawbacks. Comprehensive knowledge of each resin type empowers dental professionals to make informed decisions that align with patient needs, leading to successful outcomes in restorative and prosthetic dentistry (Prpić et al., 2020).

2.4 Conventional Fabrication of Denture Base

The conventional denture fabrication workflow involves several key steps. It begins with taking accurate impressions of the edentulous arches, followed by creating a master cast. Bite registration captures the relationship between upper and lower arches, and a wax try-in allows for adjustments before the final denture setup. The wax try-in is then invested in a flask, filled with acrylic resin, and cured. After deflasking and finishing, the denture teeth are set and secured in the denture base. The denture is further refined and polished before being fitted to the patient and delivered.

This method of denture fabrication has been a staple in dentistry before the emergence of digital technology (Dimitrova et al., 2022). However, compared to the digital denture fabrication method, the conventional approach has several disadvantages. Firstly, conventional fabrication relies on manual techniques and requires extensive human labour, which can introduce human errors, leading to inaccuracies in fit and occlusion (Reymus et al., 2020). Additionally, the time required for each step, including impressions, model preparation, and physical adjustments, can result in extended chairside and laboratory time. These prolonged timelines can lead to patient discomfort, as they have to endure multiple appointments (Alauddin et al., 2021).

Another significant disadvantage is the potential for material distortion during the curing process, especially in heat-cured methods. The acrylic resin's polymerization generates heat, which can lead to warping and affect the dimensional accuracy of the denture. Furthermore, conventional denture fabrication often involves the use of physical molds and models, which require considerable physical storage space and can degrade over time (Prpić et al., 2020). Additionally, transferring these molds to a dental laboratory will involve an additional cost and might also be subject to distortion during transportation or handling.

Moreover, the denture fabricated with the conventional approach was often reported with lacking in precision and efficiency (Tahayeri et al., 2018). The inaccuracy in the denture fit can greatly affect the patient's comfort and satisfaction. Since the conventional approach involves extensive human labour and manual handling, the entire workflow is more intricate, demanding the expertise of a certified dental professional to operate. In addition, the manual nature of conventional fabrication limits the ability to incorporate intricate designs, textures, and advanced features such as hollowed models.

2.5 Digital Fabrication of Denture Base

With technology moving faster than ever before, the manufacturing industry has been introduced to the Industrial Revolution (IR), whereby production was digitalized and designed to be automated with the minimal involvement of human labour. The advantage of the digitalization of the industry is to reduce possible human error, increase productivity, and reduce the necessity of redundant storage (Vasamsetty et al., 2019; Al-Dwairi et al., 2023). Given the inherent distinctness of each individual's oral contours, the demand for personalized oral prosthetics is evident. This distinctiveness underscores the necessity for custom-designed solutions for every patient, rendering digital technology a preferred method for addressing this intricate task.

The digital method of denture fabrication represents a technological advancement that revolutionizes the traditional approach, introducing precision, efficiency, and customization through Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM) technology. This contemporary approach replaces many manual steps with digital processes, streamlining the workflow and enhancing the overall quality of the denture (Srinivasan et al., 2021; Fouda et al., 2022).

In the digital method, the process begins with a digital impression, captured using an intraoral scanner that creates a 3D virtual model of the patient's edentulous arches. This digital model is then transferred to computer software equipped with CAD tools. Here, the dental professional designs the denture base, tooth arrangement, and occlusion using digital tools. This step offers an unprecedented level of customization, allowing for precise placement of denture teeth, accurate fit to oral contours, and intricate detailing (Lin et al., 2020).

Once the design is complete, the CAD software generates a digital blueprint that serves as the basis for the manufacturing process. This phase of computer-aided manufacturing (CAM) encompasses two distinct production approaches, subtractive manufacturing (SM) and additive manufacturing (AM). Subsequently, the designed denture is translated into physical parts based on the digital blueprint. This manufacturing process can produce a denture base characterized by exceptional accuracy and uniformity, reflecting the intricate details of the original digital design.

The integration of CAD-CAM technology not only eliminates many of the manual steps prone to human error but also significantly reduces the time required for fabrication. It also allows for rapid adjustments and modifications without the need for remaking physical molds or models, thus enhancing efficiency and patient satisfaction.

Furthermore, the digital process ensures a high level of reproducibility, resulting in consistent and predictable outcomes (McLaughlin et al., 2019).

The greatest advantage of digital technology is the ability to incorporate intricate designs, textures, and advanced features with exceptional accuracy. Complex patterns and textures are digitally sculpted with precision, guaranteeing a consistent replication of these intricate details across different denture bases. Moreover, digital denture fabrication can integrate sophisticated mechanical components and interlocking features, all seamlessly executed through the precise control of CAD-CAM technology.

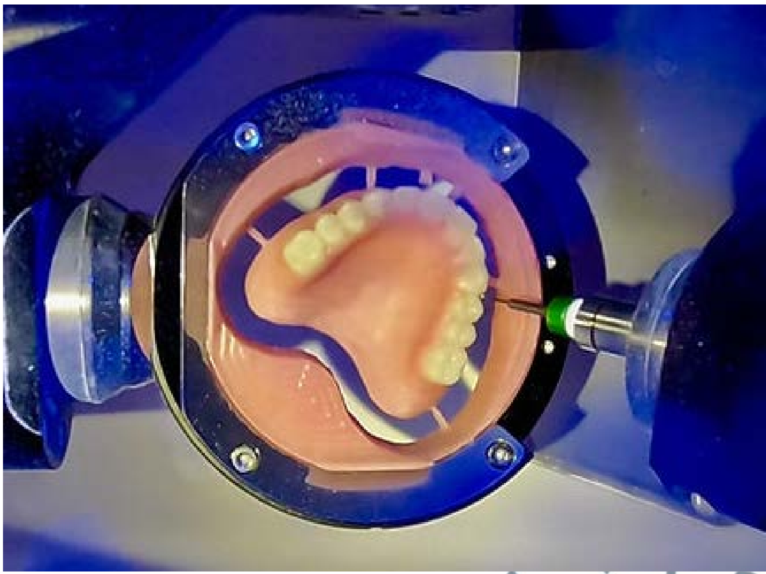
2.5.1 Subtractive Manufacturing

Subtractive manufacturing (SM) is a production process that involves the removal of material from a solid block or workpiece to achieve the desired shape and dimensions. This method involves cutting, drilling, milling, or grinding away excess material until the final product is attained. With the advancement of digital technology, the incorporation of Computer-Aided Manufacturing (CAM) has brought significant advancement to subtractive manufacturing. This progress is particularly notable through the adoption of Computer Numeric Control (CNC) technology. CNC technology empowers the automation of subtractive manufacturing processes, allowing denture fabrication to be exceptionally accurate and consistent. This automation enhances the overall efficiency of the manufacturing process by introducing a streamlined process and consistently delivering uniform results (Al-Dwairi et al., 2023).

SM can create complete shapes effectively but at the expense of excessive material being wasted. Due to the principle of subtracting milling of removing material from a prefabricated blank to form desired shape and size, this method of fabrication requires the removal of excess material, often resulting in significant waste. Approximately 90% of a prefabricated block is removed to create a typical dental restoration (Aati et al., 2022). Excessive waste materials are often associated with several consequences, for instance, higher fabrication costs. As there are more materials required to produce a single prosthesis, it could lead to a higher cost for the dental laboratory or practice (Fouda et al., 2022). This can have a direct impact on the cost of the final prosthesis for the patient, which can make it less accessible to those who cannot afford it.

Moreover, the milling process involved the wearing of burs, and the limitation of tool paths has constrained the product geometry SM can produce (Bae et al., 2017). As a result of which, SM is not favourable when it comes to fabricating dental prostheses with complex geometries and contours such as the denture base which comprises many ridges and troughs. Although this drawback has been addressed and can be resolved by involving an advanced milling machine with 5-, or 6-axes, the cost efficiency of this approach is poor as the involvement of advancement machining is very costly (Fouda et al., 2022).

While many patients who suffer from edentulism usually have low socioeconomic status such as unemployment, no health insurance, low educational attainment, and low income, they would not be able to bear an exorbitant price to have their oral disparities treated (Mitchell et al., 2013).



Source: https://www.venusdentureclinic.co.nz/single-post/2019/01/10/digital-vs-conventional-dentures

Figure 2.4: Subtractive milling of complete denture

2.5.2 Additive Manufacturing

Alternatively, additive manufacturing (AM), also known as three-dimensional (3D) printing, is a revolutionary production approach that constructs objects layer by layer from raw materials. This stands in contrast to subtractive manufacturing, where the material is removed from a solid block. In AM, digital 3D models are sliced into thin horizontal layers, and these layers are sequentially built up to form the final object. This method allows for intricate and complex geometries that may be challenging to achieve through traditional means (Tian et al., 2021).

Since the invention of the first 3D printing technology, Stereolithography (SLA) in 1964, numerous 3D printing technologies have been pioneered (Jockusch & Özcan, 2020). In dentistry, several 3D printing technologies were commonly practised owing to their low initial cost, fast fabrication, high precision, and suitable raw material (Prince, 2014; Yue et al., 2015). Among the commonly used AM technologies in dentistry are vat polymerization, selective laser sintering, and material jetting. These technologies share the fundamental principle of additive layering, but their mechanisms and materials differ from each other.

3D printing builds up an object from nothing to something directly from its raw materials, in the case of dentures, the raw materials are usually PMMA or dimethacrylates (Prpić et al., 2020). In contrast with the SM, 3D printing produces little to no wastage during production, saving cost while at the same time being environment friendly. Additionally, since the AM doesn't require as much mechanical contact as the SM, the maintenance, processing, and initial cost of the AM is significantly lower than SM. When it comes to productivity, 3D printing allows simultaneously printing multiple objects at once. Multiple dentures, dental arches, crowns, and surgical guides can be printed all at once as long as the objects fit in the build volume of the 3D printer (Borrello et al., 2018). Since the whole printing process is automated, human interference are minimal during the entire process of fabrication. Human technicians will only take place in the design, preparing and post-processing phase, including design of the denture with CAD software, prepare the 3D printer, removed the printed part from the platform, and subsequent post-processing.

However, the mechanical and biological attributes of 3D-printed dentures have been observed to fall short of those fabricated through subtractive manufacturing (SM). This discrepancy primarily stems from a lower degree of conversion in the 3D-printed dentures. As a response, extensive research has been undertaken to enhance this conversion level. This includes incorporating filler particles into the resin matrix, post-curing the 3D-printed part with optimized duration, optimizing printing parameters and others (Ai et al., 2017; D. Kim et al., 2020; P. Li et al., 2021; Aati, Aneja, et al., 2022).

Notwithstanding, it's important to note that both digital methods, SM and AM have demonstrated superior outcomes in terms of mechanical and biological properties when compared to conventional denture fabrication (Hada et al., 2021; Keßler et al., 2021). A recent study reported that denture wearers have a higher level of satisfaction towards the 3D-printed denture base as it provides better retention and stability (Tasaka et al., 2019). This showcases the reliability and significant potential that digital technologies hold in the field of dentistry. As these technologies continue to evolve and refine, they have the potential to reshape the landscape of denture fabrication for enhanced patient care (Alhallak et al., 2023).

Source: Retrieved from https://www.osdentlab.co.uk/products/digital-dentures/

Figure 2.5: 3D printing denture bases

2.5.2.1 Vat Polymerization

When it comes to denture fabrication, vat polymerization is the preferred method of fabrication owing to its ability to produce high-accuracy dentures swiftly and cost-effectively (Lee et al., 2023). Vat polymerization, often referred to as photo-curing 3D printing, operates on the principle of photopolymerization. In this process, photosensitive resin is activated and polymerized through exposure to UV or visible light. It is one of the most mature 3D printing technologies and is widely used in fabricating dental prostheses. The first ever 3D printing technology that has been developed, SLA, was categorized under this technique. Aside from SLA, digital light processing (DLP), and liquid crystal display (LCD), are the other members that were categorized under the vat polymerization technique. While all these techniques operate on the principle of photopolymerization, each technique's approach to polymerization diverges from the others, resulting in distinct advantages and challenges (Mohamed et al., 2019).

These vat polymerization techniques can have two different configurations, the free surface approach also known as bat configuration and the constraint surface approach or bath configuration, each differentiated by the movement of the build platform. In the "Bat" configuration, the build platform ascends from the bottom, while in the "Bath" configuration, it descends from an upside-down position. Both configurations share key components in their machine setup, including a vat or reservoir tank, a built platform, a light source, and an imaging system. An important distinction lies in the presence of a flexible film affixed to the bottom of the vat in "Bat" configuration machines, whereas the "Bath" configuration lacks this component (Figure 2.6).

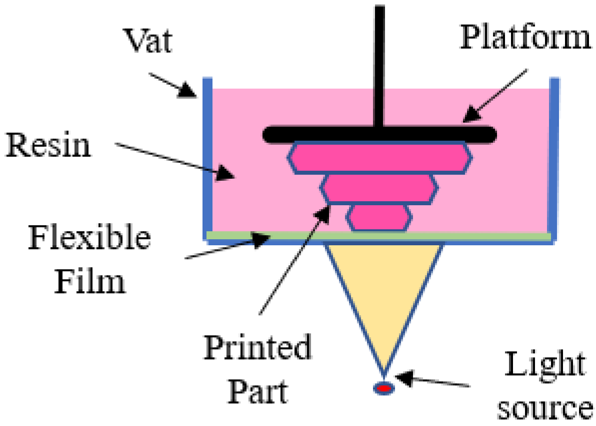


Figure 2.6: Free Surface Configuration (Bat)

In the printing process of "Bat" configuration machines, the vat is initially filled with liquid photosensitive resin. The build platform then descends to the bottom of the vat, coming into slight contact with the flexible film and leaving a thin layer of resin between them. Upon activation of the light source, the photopolymerization process begins, causing the thin layer of resin to cure. As the build platform subsequently moves upward to create the next layer, the solidified resin layer remains adhered to it but detaches from the flexible film. This process is repeated with each successive layer, and the build platform will continue to move upwards after the curing of each layer, away from the vat. Eventually, all layers are cured, resulting in the printed object adhering to the build platform in an upside-down orientation (Lee et al., 2023).

On the other hand, in the "bath" configuration, a contrasting approach is taken. In this approach, the light source is positioned at the top, allowing it to cure the resin within the vat from an overhead position (Figure 2.7). In this setup, the build platform moves inwards into the vat after forming each layer. Unlike the "Bat" configuration, there is no requirement for a flexible film in the "Bath" configuration, as the thin layer of liquid resin is cured directly onto the layer before it. Nonetheless, this configuration does present a distinct challenge in the form of potential chemical reactions with the ambient air. Given that the printing layer is directly exposed to the surrounding environment, there's an increased risk of unintended chemical interactions occurring. As a result, the "Bat" configuration is more frequently adopted in the 3D printing industry, as it circumvents this challenge and promotes a more controlled curing environment compared to the "Bath" configuration (Waheed et al., 2016).

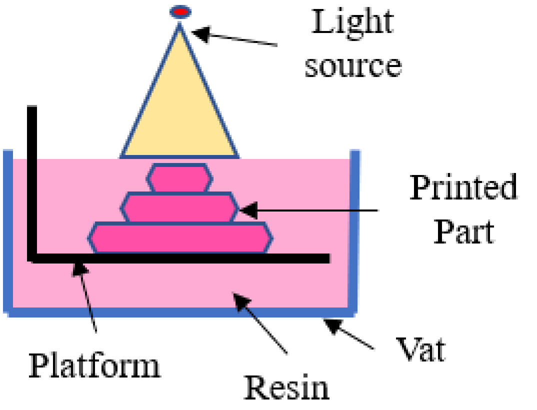


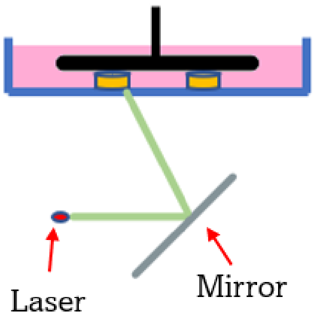
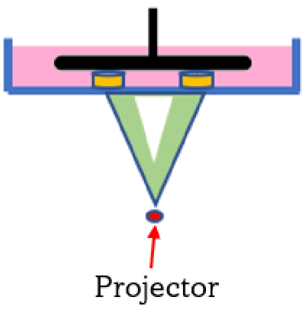
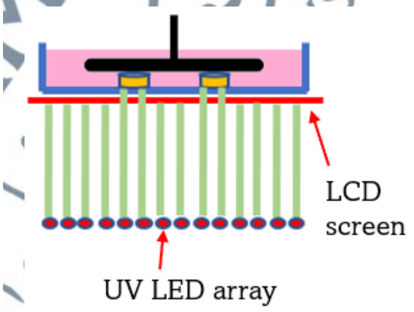
Figure 2.7: Constraint Surface Configuration (Bath)

While these two configurations share several similarities, their key distinction lies in their mechanisms and imaging systems. In SLA, an ultraviolet (UV) laser beam serves as the light source for resin polymerization. This UV laser is guided by a mirror and a galvanometer, allowing it to be precisely directed onto the liquid resin's surface, effectively curing the path corresponding to the cross-sectional pattern it follows (Koch Scotti et al., 2020). As a result of this approach, SLA printers can theoretically accommodate larger print volumes (Dizon et al., 2018). However, the printing speed of SLA is relatively slower due to its reliance on a single moving laser beam for curing. This aspect means that larger printing parts necessitate more time for completion. Although it is feasible to print multiple parts simultaneously, the overall printing time increases accordingly.

DLP, in contrast, utilizes a high-resolution projector as its light source for the resin-curing process. Much like the projectors used in theatres, a DLP projector projects an image of the intended cross-sectional area of the printing part onto the liquid resin. This projection ensures that the entire cross-sectional layer is cured simultaneously. The key element of this projector is the digital mirror device (DMD). DLP technology benefits from its advanced electronics, granting it an impressive printing resolution (He et al., 2018). However, it does come with a significant limitation in terms of build volume. To achieve the desired high printing resolution, the DLP projector needs to be positioned close to the exposure plane to prevent pixel dilation. This restriction on the placement of the projector is a trade-off for achieving optimal printing resolution (Chang et al., 2012). As a result, the DLP technique excels in providing high printing resolution and speed, making it particularly suited for creating smaller parts (Quan et al., 2020).

The liquid-crystal display (LCD) technique is notably akin to the DLP technique but with a distinctive difference in the imaging system. This technique employs an LCD screen as its imaging system instead of a DMD. On the other hand, a UV light-emitting diode (LED) array is deployed as the light source to initiate the polymerization of the liquid resin. The printing process begins with the exposure of the UV LED array, at the same time, the LCD panel will mask off the unprinted area, only allowing light to pass through the unmasked cross-sectional area and cure the entire layer at once (Shan et al., 2020). However, during the printing process, a small number of liquid crystal molecules will fail to rearrange and cause a small amount of light to bleed through the LCD panel. As a result, this technique will have a lower dimensional accuracy since the light bleed through the LCD can cause over-curing on the printed part (Lee et al., 2023). While the LCD approach offers satisfactory performance and precision, it falls short compared to the DLP technique in these regards. This divergence highlights the distinctions between these two techniques' capabilities. Despite this performance gap, the LCD technique boasts an attractive feature in its affordability. Furthermore, it offers a good printing resolution and a rapid printing rate (Mohamed et al., 2019). This balance of cost-effectiveness and performance renders the LCD method a viable and pragmatic option for additive manufacturing applications.

Table 2.1: Schematics and Attributes of Various Vat Polymerization Techniques

Stereolithography (SLA)	Digital Light Processing (DLP)	Liquid Crystal Display (LCD)
		
Decent precision	Excellent precision	Adequate precision
Scalable print volume	Small print volume	Adequate print volume
Slow printing rate	Swift printing rate	Adequate printing rate
Layers were cured line-by-line	The entire layer was cured at the same time	The entire layer was cured at the same time

Source: (Lee et al., 2023)

Various factors can influence the physical, mechanical, and biocompatibility attributes of 3D-printed dentures. These factors include layer height, material, printing orientation, printing technology and others a(Zhang et al., 2019; Unkovskiy et al., 2021; Wang et al., 2021; Al-Qarni & Gad, 2022). In a recent study, a comparison was conducted on the flexural properties and cytotoxicity of interim materials produced using DLP and LCD technology (Chen et al., 2021). The findings suggested that the photosensitive resin designed for DLP 3D printers could be effectively employed on an LCD printer with suitable settings. Notably, LCD-printed interim materials exhibited comparable flexural properties to DLP-printed counterparts when post-polymerization was appropriately managed. Another investigation scrutinized the flexural properties and accuracy of distinct 3D-printed denture base resins via SLA and DLP printers (Al-Qarni & Gad, 2022). While the SLA printed part exhibited higher accuracy error compared to DLP, their flexural strength remained akin. However, ambiguity arose due to the use of diverse proprietary resins, which made it unclear whether the mechanical properties were influenced by the material or the printing technology.

Additionally, a recent study explored the surface hardness of 3D-printed orthodontic aligner materials printed by LCD and DLP techniques (Zinelis et al., 2022). It suggested a slightly superior hardness was achieved from the LCD approach, though variations were expected due to the different materials used. Similarly, another study focused on the surface roughness and hardness of a 3D-printed denture base printed with two different DLP printers with different printing orientations (Al-Dulaijan et al., 2022). The results showed that surface roughness remained unaffected, while different DLP printers did influence surface hardness. Although numerous studies have established the influence of printing resin and post-curing settings on mechanical properties (Srinivasan et al., 2021; Unkovskiy et al., 2021; Aati, Akram, et al., 2022; P. Li et al., 2022), an in-depth exploration of the effect of various vat polymerization printing techniques is absent. Thus far, despite some studies characterizing 3D-printed denture base properties, there is a paucity of data in the existing literature regarding the impact of the 3D-printed denture base when produced using different vat polymerization techniques.