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3D Printed Complete Dentures - Current Status and Clinical Performance

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ABSTRACT

Applications of additive Computer-aided design and Computer-aided manufacturing (CAD/CAM) technology are exponentially expanding to include multiple fields in prosthodontics. 3D printing of complete dentures is developing at such a rapid pace, that this technology might be in the near future an approved integral part of the rehabilitation of complete edentulism. The objective of this study is to cast light on additive CAD/CAM technology in complete denture prosthodontics. Findings of in-vitro investigations, in addition to clinical- and patient- centered studies are analyzed. Advantages, limitations and prospects are discussed. An electronic followed by manual search of relevant literature in English was conducted. Relevant keywords were used to search in bibliographic databases. Predetermined inclusion and exclusion criteria were utilized to extract the relevant research titles. Both authors then screened the abstracts of the selected titles. The last step was analyzing the full articles to extract the data. The extracted material was then categorized under headings in a narrative review of literature format. It was concluded that workflows of 3D printed complete dentures are being continuously refined. The physical, mechanical properties and material biocompatibility of printed complete denture materials are also been improved. Advantages of this technology include potential cost reduction, fabrication of complex geometries, possible reduction in number of visits, archivability, apparent acceptable accuracy, less post-insertion maintenance and acceptable patient satisfaction. On the other hand, some aspects still need further investigations and improvements namely: color stability and esthetics, wear resistance of the occlusal surfaces, amenability to rebasing and relining, in addition to surface roughness and Candida albicans adherence.

Keywords: Additive manufacturing, 3D printing, Rapid prototyping, CAD/CAM, Complete dentures.

1. Introduction

Complete dentures represent a treatment option that is indispensable for edentulous patients who are contraindicated or cannot afford implant therapy. The current conventional complete denture fabrication technology has been used for over 100 years. It requires lengthy laboratory steps and the skillful manipulation of materials with a number of inherent processing errors, inaccuracies in addition to the expenses (Jacob, 1998; Bidra *et al.,* 2013; Abdelnabi and Swelem, 2017).

Computer-aided design and computer-aided manufacturing (CAD/CAM) is a technology that is currently implemented in complete denture fabrication and is rapidly evolving. Computer-aided technology includes subtractive and additive manufacturing technologies. In subtractive manufacturing the images of the digital file are used to physically remove material by cutting and milling to achieve the geometry of the desired product. In additive manufacturing, images from a digital file are used for 3 dimensional printing by laying down layers of selected material to create the product (Wagner *et al.,* 2021; Goodacre and Goodacre, 2022).

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The first English scientific report on the concept of utilizing Computer aided Technology to fabricate complete dentures was published by a group of Japanese researchers. Their article described using rapid prototyping technology to construct complete dentures from photo-polymerized composite resin material (Maeda *et al.,* 1998). Inokoshi *et al.,* (2012) are also among the leading researchers, who demonstrated the clinical efficiency of additive manufacturing techniques. Tae Kim in 2010 founded one of the pioneer companies that offered a workflow for fabricating 3D printed dentures. In 2016 his company offered the first definitive printed dentures (Wagner *et al.,* 2021).

In the study at hand an electronic followed by manual search of relevant literature in English language was conducted independently by the two authors. The following bibliographic databases were searched: MEDLINE, Embase, Cochraine and Google scholar up till June 2022. Keywords used in the search included: 3D printed dentures, rapid prototyped dentures, CADCAM dentures, CAD-CAM dentures, CAD/CAM dentures, digital dentures, dentures. Inclusion criteria were as follows: 1. Articles that compared 3D printing to other complete denture fabrication techniques; 2. Articles that investigated different technologies and settings used in printing denture bases. 3. Publications in peer-reviewed journals; 4. English language articles. Exclusion criteria were: 1. Publications that included repetitions of included articles; 2. Articles that did not meet the inclusion criteria.

2. *In-vitro* studies

2.1. Flexural mechanical properties

Flexural strength is an important mechanical property that is commonly used to compare newly introduced denture base materials to the conventional heat cured acrylic resin (Goodacre and Goodacre, 2022). The commonly used testing method is three-point bending (Srinivasan *et al.,* 2021a).

Some studies compared conventional, milled, printed and polyamide denture bases. Prpic *et al.,* (2020) compared the flexural strength of three brands of conventional heat polymerized polymethyl methacrylate with another three brands of CAD/CAM milled resins, one 3D printed variety and one polyamide denture base material. Milled CAD/CAM resins and polyamide showed the highest flexural strength while the 3D printed variety had the lowest values. The milled materials had superior mechanical properties. However, there were variations between the different brands and thus it was concluded that the method of polymerization per se does not guarantee optimal mechanical properties. Variations between different brands have also been reported by Steinmesl *et al.,* (2018a). Zeidan *et al.,* (2022) also evaluated the flexural strength of two brands of CAD/CAM milled denture base resins, two 3D printed brands, one conventional compression molded heat polymerized resin and a polyamide variety. In partial agreement with the results of Prpic *et al.,* (2020), they reported that the CAD/CAM milled resins had the highest flexural strength. On the other hand, 3D printed and polyamide resins displayed the lowest flexural strength values.

Fiore *et al.* (2022) compared the flexural properties of 3D printed, CAD/CAM milled and heat polymerized polymethyl methacrylate (PMMA). The assessed mechanical properties were: ultimate flexural strength, flexural modulus and flexural strain percent at flexural strength. CAD/CAM milled resins displayed superior flexural properties in most of the tested parameters. It is worth mentioning that 3D printed resins showed the highest flexural strain percent at flexural strength.

Srinivasan *et al.* (2021b) evaluated the flexural strength and other mechanical properties of CAD-CAM milled and 3D printed resins used in complete dentures. They analyzed the effect of using 3D printers recommended by the manufacturer with third party printers. Vertical and horizontal build orientations were compared. The assessed variables were: ultimate strength, elastic modulus, toughness, yield point and strain at yield point. Milled resins showed superior ultimate strength, elastic modulus and toughness. Differences in yield point and strain at yield point were insignificant. The elastic modulus and ultimate strength of resins printed with printers recommended by the manufacturer were significantly higher than those with third party printers. Specimens printed with vertical orientation showed significantly lower modulus of elasticity.

Al-Quarni and Gad, (2022) compared the flexural strength and the modulus of elasticity of three brands of 3D printed resins to conventional heat polymerized polymethylmethacrylate denture base material. The heat polymerized material showed both higher flexural strength and modulus of elasticity. Similarly, Chhabra *et al.,* (2022) compared the flexural strength of 3D printed resins to conventional heat cured denture base material. Their results are in accordance with those of Al-Quarni and Gad, (2022).

Shim *et al.* (2020) investigated the effect of build angle on flexural strength. Printing orientations were 0, 45 and 90 degrees. The highest flexural strength was reported with 0° followed by 45° then 90°. Srinivasan *et al.,* (2021b) compared horizontal (0°) with vertical (90°) build orientations. Their results are in accordance with those of Shim *et al.,* (2020) as the horizontal orientation had the better flexural properties.

It could be deduced from the above-mentioned studies in addition to systematic reviews and meta-analyses conducted by Srinivasan *et al.,* (2021a) and Abulsaud and Gad, (2022) that CAD/CAM milled resin denture base material have superior flexural properties. These favorable features could be attributed to the manufacturing technique of PMMA pucks that is carried out under pressure and temperature compared to other techniques (Srinivasan *et al.,* 2021b). The improved mechanical properties make it possible to use the milled variety in thin dimensions without fearing fracture (Goodacre and Goodacre, 2022).

It is however worth mentioning that despite the lower values of flexural strength of 3D printed resins, this category of denture base resins can still achieve the minimum ISO requirement of 65 MPa (Prpic *et al.,* 2020; ISO 20795, 2013)

2.2. Denture base accuracy

Another aspect that needs more clinical evidence to support the in-vitro findings is accuracy and adaptation of printed dentures. One of the important features used to promote digital technology in complete denture fabrication is the better fit. Intimate contact between the denture base and the denture bearing tissues is crucial for retention (Jacobson and Krol, 1983 ; Murray and Darvell, 1993). A number of studies reported superior intimate fit, lack of distortion, higher accuracy and intaglio surface reproducibility of milled dentures in comparison to the conventional pack and press, pour and injection molding technique (Goodacre *et al.,* 2016; Steinmassl *et al.,* 2018b; Wang *et al.,* 2021). Al-Helal *et al.,* 2017 in a clinical study showed the superior retention of milled denture bases in comparison to the conventional heat cured variety. The question is how does the two varieties of digital manufacturing techniques (milled versus printed) compare to each other. Tasaka *et al.,* (2019) in an in-vitro study compared accuracy and retention of heat cured versus 3D printed denture bases. Greater accuracy and higher retentive forces were reported with the printed bases. The authors interpreted their results by the reduced amount of lifting of the dentures from their models with printing. This feature is attributed to the 3D printing fabrication technique of consecutive photo-polymerizing of thin layers. This resulted in better border seal and more uniform pressure on the supporting structures, which ultimately resulted in better retention. The findings of Ogle *et al.,* (1986) confirmed the better fit of the light-cured in comparison to the heat-cured resins. Lee et al, (2019) findings are in accordance with Tasaka *et al.,* (2019) in concluding that dentures bases fabricated by digital technologies- both milled and 3D printed - produced better fit in comparison to those fabricated by analog technology. A number of studies agreed that accuracy of both subtractive and additive digital technologies used for complete denture fabrication are acceptable if not superior to that of the conventional techniques (Ucar *et al.,* 2012; Chen *et al.,* 2015; Pereyra *et al.,* 2015; Kattadiyil *et al.,* 2015; Bidra *et al.,* 2016; Goodacre *et al.,* 2016 ; Srinivasan *et al.,* 2017; Srinivasan *et al.,* 2018;;Steinmassl *et al.,* 2018b; Srinivasan *et al.,* 2021a).

Comparing and contrasting milled to 3D printed denture base accuracy and trueness seem to be in favor of milled dentures but still show controversy (Wagner and Kreyer, 2021; Goodacre and Goodacre, 2022). Kalberer *et al.,* (2019) demonstrated in an in-vitro study the better trueness of the milled in comparison to the printed complete dentures. The authors considered the possible clinical impact of their results to be debatable, as a number of studies considered the level of accuracy provided by printed dentures to be acceptable (Inokoshi *et al.,* 2012; Ucar *et al.,* 2012; Pereyra *et al.,* 2015; Chen et al.; 2015). The reduced trueness of the printed complete dentures could be theoretically related to the polymerization shrinkage that takes place in the rapid prototyping workflow. Printed material does not polymerize completely until the final post processing procedure. Initial demounting of the partially cured complete dentures from the printer platform can result in deformation. Moreover, the uncured residual resin layer that has to be removed by rinsing in a suitable solvent can also add to the reduced trueness. Findings of Hsu *et al.,* (2020) are in accordance with those of

Kalberer *et al.* (2019) showing the better accuracy of milled in comparison to the printed dentures. They contributed their results to the increased flexibility of dentures produced by additive manufacturing techniques. Ucar *et al.,* (2012) pointed out to the possibility of long term dimensional instability of rapidly prototyped light-polymerized resins. To the best of the authors' knowledge, there are no publications investigating that aspect.

In contrast to the above-mentioned studies, Hwang *et al.,* (2019) found that printed dentures have higher trueness when compared to the milled variety. They emphasized that accuracy is affected by variables as printing geometry, technical design and the resin used. These factors have an impact on the distortion that may take place during post-processing secondary curing. Alharbi *et al.,* (2017) and Shim *et al.,* (2020) demonstrated that accuracy varies based on the printer technology and software configuration that controls the polymerizing light source. You *et al.,* (2021) investigated the effect of different layer thicknesses of the printed dentures on accuracy of both cameo and intaglio surfaces. 100µm layer thickness resulted in a better range of acceptable deviations of the intaglio surface. 50µm thickness showed improved accuracy of the cameo surface. They concluded that 100µm appears to be acceptable. It is worth mentioning that the thicker printing layer setting results in faster printing.

2.3. Esthetics and color stability

Esthetics and color stability of printed denture materials is a field that needs further improvements. Existing literature still lacks long term clinical studies. Gruber *et al.,* (2021) compared in an in-vitro study color changes of conventional, milled and printed denture base materials. The specimens were subjected to thermal aging and immersion in different liquid media namely, distilled water, red wine and coffee. Significantly higher color changes were reported for the printed resins. The authors correlated decreased color stability to relative high water sorption of printed resins. Berli *et al.,* (2020) conducted a study that showed the increased water sorption of 3D printed denture base materials. Goodacre and Goodacre, (2022) added that surface deterioration and subsequent color instability can also be attributed to variables as mixing, polymerization and post-processing procedures. These findings are in accordance with a randomized survey that compared the appearance of conventional, injection molded, milled and printed complete dentures (Stilwell *et al.,* 2021). The evaluators included undergraduate dental students, postgraduate dental residents, dental technicians and elder complete denture wearers. Printed dentures showed the lowest scores by both the dental professionals and denture wearers. On the other hand, an in-vitro study did not support the inferiority of color stability of printed resins. Alfouzan *et al.,* (2021) compared color stability of conventional and 2 printed denture resins. Specimens were immersed in staining media, aged by thermal cycling and subjected to mechanical brushing. The experimental conditional simulated a 1 to 2 years of use. It was concluded that color changes were low in comparison to conventional polymethylmethacrylate.

2.4. Biocompatability

Studies investigating biocompatibility, potential allergenicity and levels of residual monomer are still limited. Biocompatibility is critical for patient safety. Adverse effects of compromised biocompatibility include pain, burning mouth sensation, hypersensitivity and allergic reactions (Kanerva *et al.,* 1997; Vilaplana and Romaguera, 2000). Unreacted monomer, residual solvents, photoinitiators and degradation products are possible sources of cytotoxicity (Mondschein *et al.,* 2017). Srinivasan *et al.,* (2021b) assessed biocompatibility of different milled and 3D printed denture base materials. Resaurin assays were used to test biocompatibility of the tested specimens on cultured human epithelial and gingival cells. No significant differences were reported between the different groups. Tzeng *et al.,* (2021) formulated five urethane acrylate based photopolymer resins for 3D printing of denture bases. MTT assay using mouse fibroblast cells was utilized. The findings were in accordance with those of Srinvasen *et al.,* (2021b), as there were no signs of cytotoxicity. Hwangbo *et al.,* (2021) investigated the effect of washing solution type and time of application on the biocompatibility of 3D printed dental resins. The washing solutions were tripropylene glycol monomethyl ether and isopropyl alcohol. Time of washing ranged from 3 to 90 minutes. Human gingival fibroblasts were evaluated for cell viability and cytotoxicity. Type of washing solution had an insignificant effect. On the other hand, increasing washing time had a highly significant positive effect on both morphology and number of the fibroblasts.

2.5. Surface roughness and adherence to Candida albicans

Surface roughness and Candida albicans (C. albicans) are important variables that are critical in evaluation of materials used as denture bases (Al-Fouzan *et al.,* 2017). It is well established that candidal colonization is an important predisposing factor for denture stomatitis (Ramage *et al.,* 2002; Coco *et al.,* 2008). A number of studies correlated surface characteristics of denture base material with the amount of adherence of the candidal biofilm (Hazen, 1989; Radford, 1998; Ramage *et al.,* 2006). A decrease in surface roughness and porosity decreased such adherence (von Fraunhofer and Loewy 2009; Bidra *et al.,* 2013). Koujan *et al.,* (2022) evaluated C. albicans adherence to milled, 3D printed and conventional heat cured PMMA denture base materials. Milled and conventional denture base materials showed less adherence compared to the printed variety. Differences between milled and conventional denture bases were insignificant. Polishability of the different denture bases is an important aspect as it is relevant to plaque accumulation. (Emami *et al.,* 2014; Koroglu *et al.,* 2016; Alammari, 2017). Kraemer *et al.,* (2020) investigated surface roughness, gloss values and scanning electron microscope images of cold polymerized polymethylmethacrylate, milled and 3D printed denture base materials. The specimens were further divided in 3 subgroups based on the surface treatment namely, untreated, intermediately polished and polished to high gloss. Additionally 3D printed specimens were either coated with liquid resin or both coated and polished. Milled specimens showed superior surface characteristics. Polishing resulted in better outcomes in comparison to coating. It is worth mentioning that the surface roughness of both polished and coated samples demonstrated clinically acceptable values as the relevant threshold of 20µm was not exceeded with either the treatments. Shim *et al.,* (2020) investigated the effect of 3 different printing orientations (0°, 45°, 90°) on roughness, surface energy, hydrophilicity and adherence of Candida albicans (C. albicans). 45° printing orientation resulted in higher roughness and surface energy. Adherence of C. albicans was highest with 0° followed by 45°and then 90°.

2.6. Bond strength to artificial teeth teeth and soft liners

Another relative limitation is the bond strength of printed denture bases to soft liners and to artificial teeth that is not as strong as to conventional denture bases (Goodacre and Goodacre, 2022). A study with conventional denture bases reported debonding of artificial teeth from the base to be the major technical problem of complete dentures. Teeth debonding represented 22 - 30% of denture repairs and took place more frequently in the anterior region (Darbar *et al.,* 1994). Choi *et al.,* (2020) studied the bond strength of denture teeth to different denture base materials namely: heat cured, milled and 3D printed. Some specimens were subjected to thermal cycling to correspond to intra oral aging of 6 and 12 months. Fracture toughness and flexural bond strength were measured. Mode of bond failure was analyzed by optical and scanning electron microscopy. Failure mode was categorized to be adhesive, cohesive or mixed. Milled and 3D printed denture bases showed lower bond strength than that of heat cured bases. Heat polymerization in contrast to 3D printing allows the formation of optimal bond between teeth and denture base with a strong interwoven polymer network. Aging did not affect bond with the milled and 3D varieties but adversely impacted the heat cured bases. The authors of the article interpreted the insignificant effect of aging in the 3D printed variety to the material homogeneity throughout the bonded structures. It is worth mentioning that the failure mode in the 3D printed variety was adhesive and specifically between the light cured bonder and the printed tooth colored resin. A possible interpretation of this mode of failure is the less efficiency of light penetration through the opaquer tooth colored printed material in comparison to the pink colored denture base resin (Monzon *et al.,* 2017).

3. Clinical and patient centered outcomes

Reviewing the dental literature revealed the limited number of clinical studies evaluating 3D printed complete dentures. This observation especially applies to randomized controlled trials.

Srinivasan *et al.,* (2021c) in a clinical randomized double-blind crossover study compared milled to 3D printed complete dentures in a sample of 15 patients. The 2 categories of digitally manufactured dentures were also compared to the old conventional complete dentures that the subjects were already wearing. A number of patient and clinical centered outcomes were evaluated. Final choice, patient satisfaction, oral health related quality of life, and willingness to pay analysis were the patient centered outcomes. Clinical outcomes included maximum bite force, chewing efficiency, clinician denture quality evaluation in addition to need for prosthetic maintenance. There were no statistically significant differences between the milled and printed varieties in most of the assessed parameters. In contrast to the study of Ohara *et al.,* (2022) patient satisfaction with the printed dentures was not inferior to the other varieties. Differences were reported only in need for maintenance and adjustment as more time, cost and visits were needed for the printed variety. Moreover, willingness to pay was higher with milled dentures. It is worth mentioning that both milled and printed dentures in the study used prefabricated teeth that were bonded to the denture bases. A clinical conventional workflow of 5-6 visits was followed. The above-mentioned points might have contributed to the favorable results reported in this study.

In another randomized controlled study, Ohara *et al.,* (2022) evaluated patient centered outcomes of 3D printed complete dentures in comparison to the conventional variety. Patient satisfaction was assessed on a visual analog scale and included retention, stability, pain, comfort, chewing efficiency, esthetics, phonetics, ease of cleaning and lastly general satisfaction. This investigation also assessed the quality of life, time needed for fabrication and subsequent adjustments as a secondary outcomes. Despite the superiority of conventional dentures in general satisfaction, comfort, stability, phonetics and ease of cleaning, some secondary outcomes including social disability and number of visits were better with printed dentures. Other outcomes showed insignificant differences. The authors concluded that despite the relative inferiority of printed dentures in both patient satisfaction and quality of life, the digital variety may be comparable in its efficiency and practicality to conventional complete dentures. It is worth mentioning that 20% of the patients preferred the printed variety.

Kim *et al.* (2021) in a retrospective study compared post-insertion maintenance of conventional and 3D printed complete dentures. Complications reported by the patients were categorized into the following items: ulcers and pain; retention problems; compromised stability; simple discomfort; discomfort with chewing or loss of retention indicative of occlusal problems; and esthetic problems. In addition, need for remakes, repairs, relines, rebases, and number and type of post-insertion adjustments were recorded. It was reported that visible ulcers and pain were less frequent with printed dentures. On the other hand, conventional complete dentures were superior in the esthetic aspect. All other items showed insignificant statistical differences. The authors attributed decreased frequency of ulcers with printed dentures to the improved internal fit of the intaglio surface. The improved fitness has been reported by the in-vitro study conducted by Oguz *et al.,* (2021), that investigated the trueness of printed dentures. It is worthwhile to mention that both the conventional and printed varieties were constructed following a 5 step construction protocol, which might have improved the outcomes with the printed complete dentures. A limitation of this study is that it covered a relatively short term duration of 1 year, with no distinction between complications occurring at the initial post-insertion period and the functional period that took place after 4 weeks of denture insertion.

Cristache *et al.* (2020) assessed Oral Health Impact Profile for Edentulous patients (OHIP-EDENT) for wearers of 3D printed complete dentures using hybrid nanocomposite polymethylmethacrylate (PMMA) improved with nano TiO2. A number of non-destructive structural and surface property tests were carried out to evaluate the effect of adding TiO2 on the homogeneity of the denture base material in addition its surface properties. These tests included scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDX), x-ray diffraction (XRD), atomic force microscopy (AFM) and micro computerized tomography (micro-CT). The aim of adding the TiO2 nanoparticles is to benefit from the antimicrobial effects, improve surface properties, and enhance thermal and mechanical characteristics. Such improvements can expand the applications of 3D printing technology to be used not only to fabricate interim but also definitive prostheses. The non-destructive tests implemented in this study showed the positive impact of adding TiO2 nanoparticles to PMMA. In addition, the authors reported a significant improvement in OHIP-EDENT after 18 months of denture use. All assessed parameters showed improvement. However, it is worth mentioning that this study lacked a control group.

Chaturvedi *et al.* (2021 b) compared in a clinical study occlusal force parameters of complete dentures constructed using conventional, milled and 3D printed techniques. Three different occlusal schemes were investigated namely bilaterally balanced, lingualized and monoplane. Assessed parameters included: centralization of forces, force distribution and maximum occlusal force percent. This study was preceded by an *in vitro* study carried out on an articulator (Chaturvedi *et al.,* 2021 a).

In the clinical study, each patient received nine sets of complete dentures divided into subsets of three based on the fabrication technique: conventional, milled and 3D printed. Each subset included 1 denture constructed following each of the previously mentioned occlusal schemes. It was reported that both the fabrication technique and the occlusal scheme impacted the occlusal force parameters. Digital complete dentures were superior to the conventional variety. Bilateral balanced and lingualized occlusion showed more favorable occlusal force parameters.

4. Prospects of 3D printed dentures

Currently, the majority of computer aided systems utilized in complete denture construction are subtractive based on milling. Nevertheless, the appealing favorable properties of the additive manufacturing techniques are promising and are expected to improve in the upcoming years (Anadioti *et al.,* 2020; Srinivasan *et al.,* 2021a).

A major advantage is the reduced cost of the printing units in comparison to that of milling machines. Reduced cost is also related to less material waste with additive technology that has a positive impact not only economical but also environmental. Simultaneous fabrication of multiple complete dentures is feasible with additive technology which results in additional cost reduction. These advantages make purchasing printers much more affordable by clinics and small dental laboratories. An additional technical advantage of printing technology in contrast to subtractive machining is the capacity to fabricate objects with complex designs and geometry (Wagner and Kreyer, 2021).

Kalberer *et al.* (2019) and Goodacre and Goodacre, (2022) shared the expectation that research will expand in a number of fields in the near future. Areas of investigation include the clinical impact of the mechanical properties, trueness, surface properties, and color stability of the printed in comparison to the milled denture bases. In addition, biocompatibility and bond strength to artificial teeth and soft liners are areas that need further assessment. It is also worth mentioning that the available clinical- and patient-centered studies of printed dentures are still limited and with short follow up periods.

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