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DIGITAL AND ESTHETIC DENTISTRY (P STATHOPOULOU AND E ANADIOTI, SECTION EDITORS)

CAD/CAM Removable Dental Prostheses: a Review of Digital Impression Techniques for Edentulous Arches and Advancements on Design and Manufacturing Systems

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Abstract

Purpose of Review The aim of this article is to provide an overview of CAD/CAM removable dental prostheses in the treatment of completely edentulous patients.

Recent Findings Computer-aided design/computer-aided manufacturing protocols continue to evolve in many areas in dentistry including removable complete dentures. Current protocols are advantageous in decreasing the number of clinical appointments needed, which may reduce the distress in elderly with limited access to care. In addition, CAD/CAM complete dentures are fabricated using standardized techniques using high-value quality controlled materials. Laboratory tabletop scanners are being used predominantly for the digitization of conventional impressions or dental casts. Further research is needed to further advance existing intra-oral scanners in digital impressioning of the completely edentulous jaws.

Summary Use of digital technology in complete denture manufacturing provides prostheses with improved quality such as reduced porosity, polymerization shrinkage, and improved retention. Presence of digital depository data allows replacement dentures to be fabricated in case they are lost or damaged.

Keywords CAD/CAM · Complete dentures · Digital denture · Edentulism

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Introduction

Diminished oral health caused by tooth loss has a great impact on individuals' well-being and quality of life. Edentulism results in impairment of masticatory function and speech, altered self-image, and social disability. Epidemiological studies have demonstrated that aging, rural geo-locality, and lower education levels are all predictors of edentulism [1]. Current demographic trends forecast an increased size and age of the senior population and that edentulism will continue to be a major oral health problem. Douglass and colleagues [2] estimated that the adult population in the USA who need one or two complete dentures is expected to increase to nearly 37.9 million in 2020. A recent news article published in 2014 by the American Dental Association reported that more than one third of Americans did not visit the dentist at all in the past year. Unfortunately, teeth extraction is often a deliberately made choice as a result of inaccessibility for care or lack of finances [3, 4]. As a result, complete denture therapy remains an important part of prosthetic dentistry [5]. Further supported by the results from a national survey of US dental practices, which estimated that approximately 9 million dentures were fabricated in 2010 [6].

The traditional methods used for fabricating complete dentures can be cumbersome as they involve multiple clinical appointments and require skilled dental technicians. Typically, five to six visits are needed to obtain preliminary impressions, definitive impressions, recording maxillamandibular relations, trial placement of the wax denture, and insertion of the finished complete dentures.

Recent efforts have been directed towards the incorporation of computer-aided design/computer-aided manufacturing (CAD/CAM) in the fabrication of dental prostheses. Maeda Y and colleagues were one of the pioneers to report on the digital production of removable complete dental prostheses in 1994 [7]. They used three-dimensional (3D) laser lithography to fabricate plastic shells of the dentition and record bases. In 1997, Kawahata et al. [8] developed a removable-denture duplication procedure using CAD/CAM with a computerized numerical control (CNC) processor and ball-end mills. Additionally, in 2009 Sun et al. [9] constructed individualized virtual flasks according to the finished CAD digital models of removable complete dentures and created individual physical flasks using a 3D printer. The dentures are finished through traditional packing procedure after artificial teeth are inserted into the flasks one by one.

CAD/CAM Components

CAD/CAM systems are mostly comprised of three main components [10] including the following:

- Data acquisition process: collected by using several technologies including contact digitization, laser scanning, or optical cameras
- Design component (CAD software)
- Manufacturing component (CAM)

Computerized aided design and manufacturing operation starts with reverse engineering (RE) [11]. This requires digitization of a given object by means of a coordinates measuring machine (CMM). Two CMM systems have been used: contact and non-contact systems. The contact CMM uses a touch probe to generate a digitized surface model from a physical model [12]. The major drawbacks for this system are that it is time-consuming and the quality of measuring can be limited for a complex surface as the size of the probe can affect sensitivity. Alternatively, non-contact digitization of surfaces using optical techniques has been developed. Here, a high-volume of data can be acquired in a relatively short time.

White light and laser 3D scanning technologies have been widely used with a very high acquisition rate and resolution (5–10 μm (ISO)).

For complete denture fabrications, laboratory tabletop scanners are being used predominantly for the digitization of conventional impressions or dental casts. While digital impressions of the mucosa may improve patient acceptance especially in patients with a severe gag reflex, intra-oral scanning of the edentulous alveolar mucosa is still not clinically feasible [13••]. This is the result of the edentulous jaws containing several zones of mobile tissue and a smooth surface covered with saliva [13••].

Intra-oral Digital Impressions

In a recent effort to evaluate the feasibility of using contemporary intra-oral scanners (IOSs) to digitize edentulous jaws, Patzelt and colleagues [13••] conducted an in vitro experiment using CEREC AC Bluecam, CEREC 3D Service Pack V3.85 (Sirona, Bensheim, Germany); Lava Chairside Oral Scanner C.O.S., Lava software 3.0 (3M ESPE, St. Paul, MN); iTero, software version 4.0 (Align Technology, San Jose, CA); and .Zfx IntraScan, software version 0.9 RC33 2.8 (manufactured by MHT Italy, Negrar, Italy/MHT Optic Research, Niederhasli, Switzerland; distributed by Zfx, Dachau, Germany). They used a tabletop scanner as reference. Their findings demonstrated highest deviations in the palatal areas with poorly traceable smooth surface appearances. Mean trueness values among the different scanners ranged from 44.1 to 591.8 μm. Faulty stitching and summation of the acquired images due to poorly differentiated structures in edentulous jaws were the likely cause for these errors [14, 15]. In addition, lack of support in edentulous patients requires the clinician to hold the scanner in a free-floating position and can result in a handshake attributing to further errors. The intra-oral scanner that achieved the best accuracy was the Lava C.O.S. System. Application of anti-reflective light powder is required for this scanner. Current research is still limited in terms of possible adverse health effects resulting from inhalation of large amounts of this powder. Furthermore, saliva and tongue movements may prohibit efficient use of this powder in edentulous patients.

Digital Manufacturing Techniques

Digital files containing the prosthetic design are used to construct the final dentures via either an additive (rapid prototyping) or subtractive manufacturing techniques (milling) [16].

Subtractive manufacturing techniques involve a milling process where the desired 3D model is obtained by removing the extra materials according to the designed digital model (CNC machining) [16]. Subtractive processes for digital dentures fabrication can either mill dentition and denture bases as one unit or as a denture base upon which denture teeth are bonded.

A possible limitation for monolithic denture fabrication is the size of the pucks that could be fitted in the milling machines. For example, the WIELAND ZENOTEC T1 milling machine can accommodate a puck that is 98 mm in diameter with a maximum height of 25 mm [17]. Due to this size limitation, it may mandate the need to mill denture bases and teeth separately and thereafter, be bonded to each other to form the complete dentures.

The 3D manufacturing through additive rapid prototyping comprises of a layering process. Commercially available prototyping machines include stereolithography apparatus (SLA), selective laser sintering (SLS), laminated object manufacturing (LOM), multi-jet modeling (MJM), and fused deposition modeling (FDM) [11]. Safety for intra-oral use of most of the currently available rapid prototyping materials remains a concern. In 2012, Inokoshi and colleagues utilized an ultraviolet-cured acrylic-based resin material for the fabrication of trial dentures (FullCure720, Objet Geometries, Rehovot, Israel), which was approved for medical use with regards to cytotoxicity and sensitization standards by the United States Pharmacopeia (USP) Class VI. The gingival tissues were created by painting the prostheses with pink composite resins [18].

Advantages of CAD/CAM Dentures and Review of Available Systems

Advantages of CAD/CAM dentures include (1) ease of fabrication and reduced time and complexity of laboratory procedures, (2) higher dimensional accuracy and standardized fabrication using high-value quality controlled materials, (3) fewer clinical appointments [19, 20, 21••], and (4) potentially less residual monomer and reduced porosity of denture bases as they are milled from pre-polymerized poly-methyl methacrylate (PMMA) under high pressure. This may reduce the harboring of microorganisms and candida leading to denture stomatitis, (5) allow for consistent thickness of the bases which can be adjusted and kept minimal for patients comfort (6), and presence of digital data depository that enables fabrication of replacement dentures in case of lost or damaged dentures [22].

CAD/CAM dentures can be fabricated in as few as two clinical sessions. This is clearly advantageous for elderly patients and those with limited access to care who find the necessity for repeated clinical visits distressing. Definitive impressions and recording maxillo-mandibular relation are typically combined in one clinical session. This is achieved by making the definitive impression and occlusal recording in either a single [19] or two separate steps [20, 23]. The second session is for the insertion of the finished prosthesis.

Some manufacturers provide stock trays that can be modified to conform to the shape of each patient's arch. Alternatively, custom trays or duplicates of patient's existing dentures may be used to make the final impressions.

Most commercially marketed digital denture systems use gothic arch tracings to record maxillo-mandibular relations; a procedure that is not commonly taught in dental schools [21••]. Arrow point tracing may be difficult in excessively resorbed and flabby ridges due to the instability of the recording bases, or in severe class II or class III skeletal discrepancies.

An extra third session for the trial denture can be added and is beneficial. This allows the clinicians to evaluate the esthetic outcomes and verify centric relations records and occlusal vertical dimension. Trial dentures for clinical evaluations may be milled from monolithic PMMA/wax as one block or with denture plastic teeth placed in the sockets. Alternatively, they may be fabricated by rapid prototyping. As the trial denture provides an exact duplicate of the fitting surface and border extensions of final dentures, it gives the clinicians an opportunity to check the retention of the denture prior to the final session. Trial dentures fabricated from monolithic material may also be given to the patient home for his/her family and friends to have input or as a spare. A key disadvantage for trial dentures fabricated as one piece (dentition and denture base) is that arrangement of artificial teeth cannot be adjusted at the chair-side [18]. Alternatively, Schweiger and colleagues [24•] reported on a workflow that provided a virtual simulated evaluation of the denture set-up through integration of an impression occlusion rim and an extra-oral face scan. A 3D face scan was made during the same appointment as the impression, whereby the patient was scanned in three different positions: neutral face with closed lips, smiling face with lips open, and face with cheek retractors and in the impression occlusion rim in place. This allowed evaluation of the teeth set-up in the absence of the patient.

Use of digital technology has also been deployed for the fabrication of custom edentulous trays. Chen et al. [25] demonstrated fabrication of a mandibular custom tray using fused deposition modeling (FDM), a kind of 3D printing technology. The CAD design was prepared using Geomagic software, where a uniform space was created for the final wash impression material. Offsets may be customized to allow for more relief in areas with bony undercuts or loose flabby tissues. They utilized polylactide (PLA), which is a renewable, non-polluting bio-resin extracted from corn and is suitable for medical use [26, 27]. The tissue surface of the digital fabricated trays provided higher accuracy and reproducibility compared to hand-made trays [25]. Several factors may affect the accuracy of the printing via FDM including [28] the filament material used, the width of the nozzle, speed of material extrusion and layer thickness, and temperature of the nozzle and the forming table. The higher the accuracy required, the longer it typically takes to finish as the material is deposited in lower thicknesses.

Similarly, manufacturing of immediate dentures can be accomplished using CAD/CAM technology [29]. Virtual bone reduction is done prior to prosthesis design. Surgical reduction guide and immediate digital dentures are fabricated simultaneously. Digital implant-planning workflows may also be integrated with the digital denture fabrication process, allowing for a complete denture that can be easily converted to an implant-supported fixed dental prosthesis [22]. The virtual implant positions as determined by the 3D implant-planning software would permit for fabrication of a conversion denture with pre-milled channels where temporary copings would be located after their attachment to the implant abutments. In addition, digital dentures are milled from a dense pre-polymerized puck of denture base resin, this allows the construction of a monolithic prosthesis (teeth and resin base as one unit), which can provide additional strength and decreased denture tooth fracture compared to traditionally fabricated dentures. This is clearly advantageous as reports demonstrated a relatively high incidence of fracture of conventional conversion dentures. Hinze et al. [30] reported a 10.8% fracture rate within the first year. Additionally, should a fracture occur, an exact duplicate can be milled using the stored digital data [22].

Currently, five commercial systems for digital complete dentures are on the market [31••]: AvaDent (Global Dental Science), Ceramill Full Denture System (Amann Girrbach AG), Baltic Denture System (Merz Dental GmbH), DENTCA/Whole You (DENTCA, Inc.; Whole You, Inc), and Wieland Digital Denture (Ivoclar Vivadent, Inc).

The Avadent (Global Dental Science) system provides clinicians with dentures fabricated by the subtractive milling process via a two- to three-appointment protocol. The system gives clinicians the flexibility to determine the means by which the definitive impression and maxillo-mandibular jaw relation records are obtained. The impressions along with the inter-occlusal records can be made using a duplicate of patient's existing dentures. The clinician may also choose to use traditional custom trays. The AvaDent system also provides the dentist with its own line of prefabricated trays that can be modified. Border molding and definitive impressions are made using a polyvinyl siloxane (PVS) material. A separate step for jaw relation record using an Anatomical Measurement Device (AMD; Global Dental Science) is made with the gothic arch tracing technique. The AMD device has an adjustable flange to provide proper lip support. The AMD trays are washed with a PVS impression material to allow for virtual alignment of the inter-occlusal records with the final impressions (Fig. 1). The manufacturer scans the impressions and provides virtual teeth alignment (Fig. 2). Trial dentures are provided per dentist's request at an additional cost. The definitive dentures can be either milled as a single unit (AvaDent XCL) (Fig. 3) or as a milled denture base with bonded denture teeth. The monolithic denture teeth are milled either as a single-layered tooth from a dentin core (XCL-1) or as a multiple layer tooth (XCL-2) which provides a more natural appearance.

Similar to the AvaDent system, the Wieland Digital Denture uses subtractive manufacturing process. The system allows for a two clinical appointments protocol with an added session if the dentist elects to have a trial session.

The Baltic Denture System (Merz Dental) uses a different approach: it is also based on only two clinical appointments, but the production of the PMMA blanks includes a standardized dental arch. Only the basal parts of these blanks are customized to the individual patient. Different tooth sizes in the blanks are used to enable patient-specific adaptation.

Fig. 1 AMD used to record maxillo-mandibular relation by the gothic arch technique. A wash impression was made to allow virtual alignment with definitive impressions

Incorporation of a digital workflow in the Ceramill Full Denture system begins with the scanning of maxillary and mandibular edentulous casts and virtual arrangement of denture teeth and waxing of the polished surfaces [32]. Wax trial bases are milled, and the modified denture teeth are inserted in the tooth sockets. Anatomical features such as rugae and stippling can be easily designed into the polished surface of the milled wax denture. The dentures are then processed using traditional methods.

On the other hand, the Dentca system uses an additive technique whereby rapid prototyping (stereolithography) is used to form a trial denture, if requested by the dentist. The definitive denture is either processed conventionally using a custom 3D printed flask or the base is printed and the denture teeth are bonded to the base.

CAD/CAM Complete Dentures Outcomes; In Vitro and Clinical Data

Studies investigating effectiveness and clinical performance of digitally fabricated dentures at this time are still scarce with the majority being clinical reports and small cohorts.

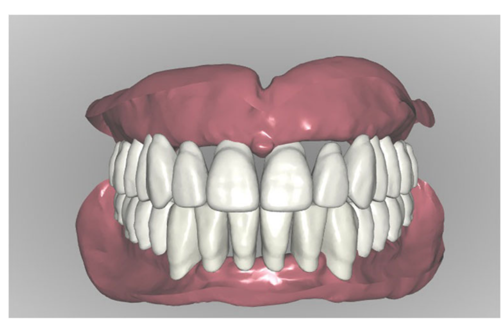

Fig. 2 Virtual alignment of teeth—frontal view

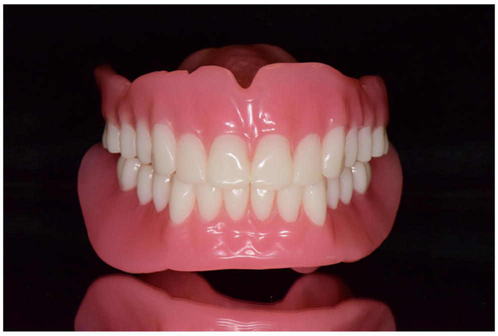

Fig. 3 Monolithic finished digital dentures

Goodacre and colleagues [33] investigated in an in vitro study the denture base adaptation of CAD/CAM dentures compared to those fabricated using traditional processing techniques (pack and press, pour, or injection). They demonstrated superior accuracy and adaptation of CAD/CAM dentures. This is important as base adaptation is a key factor in achieving retention for complete removable dental prostheses. In a clinical evaluation of retention of denture bases fabricated by heat-polymerized technique compared to CAM processing, AlHelal [34•] demonstrated significantly greater retention for the digitally milled maxillary dentures irrespective of arch form and type. Polymerization shrinkage using heat-polymerized resins which influences denture base adaptation [35] is eliminated with CAD/CAM dentures as they are milled from pre-polymerized PMMA resin pucks. Enhanced physical properties due to the increased length of polymer chains and reduced porosity with high pressure and temperature can be clinically advantageous. Ultimately, this would allow fabrication of dentures with reduced thickness providing enhanced patients' comfort [36].

A recent prospective trial evaluated the clinical and patient-centered outcomes for CAD/CAM monolithic dentures (AvaDent dentures) fabricated in two visits [37•]. They utilized a duplicate denture protocol to make dentures for 20 completely edentulous patients (40 arches). Patients were seen for an average of 3.3 visits for post-operative adjustments. Median ratings for clinical and patient-centered outcomes including retention, stability, esthetics, speech, ability to eat, and overall satisfaction were favorable at the 1-year recall.

Furthermore, Schwindling et al. [38] compared the clinical feasibility and effectiveness of two digitally designed complete dentures. Five patients participated in this study and each received a denture that was either milled from PMMA pucks or fabricated by injection molding. Dentures were designed using the Weiland Dental Digital Denture system. Both types of digitally designed dentures had similar functional outcomes with a very good esthetic rating. However, the retention of the maxillary denture was rated slightly better for the milled complete dentures. Additionally, occlusion for the milled complete dentures was rated better than the ones fabricated by injection molding. A bilateral balanced articulation was not achieved for either technique and both required intra-oral adjustments.

Moreover, Saponaro and co-workers [39] reported clinical findings using a retrospective cohort from patients, who were treated by pre-doctoral and graduate students using the two-appointment digital denture protocol (Avadent). Their study included a total of 48 patients: 24 treated by pre-doctoral students and 24 by graduate prosthodontics residents. Of the 48 patients, 17 needed additional visits due to complications on the insertion day. Five participants required a remake using the conventional methods. Lack of retention was the most encountered complication in these patients. The authors contributed this to possibly improperly made definitive denture impressions by the students. Relining the complete dentures was used to overcome this clinical problem. Increased occlusal vertical dimension was the second most commonly encountered problem. This required either a clinical remount or a remake of these dentures. Furthermore, these patients were also surveyed with regards to their satisfaction [40]. Patients were generally satisfied with the final outcome and experience. Prospectively, Kattadiyil and co-workers [21••] compared clinical treatment outcomes, patient satisfaction, and dental student preferences for digitally and conventionally processed complete dentures. Patients reported significantly higher ratings for digitally milled dentures with regards to their overall satisfaction and retention. Additionally, students preferred CAD/CAM dentures due to less clinical time required as compared to the conventional methods. Faculty assessments revealed higher scores for the digital complete dental prosthesis relative to denture base extension, contours, fit, retention, stability, and overall result.

Conclusion

CAD/CAM complete removable dental prostheses have been reported with promising outcomes and several advantages over the conventionally fabricated ones. The number of clinical appointments required can be as few as two appointments, which has a positive impact for both patients and clinicians. In addition, the depository of digital data allows replacement dentures to be fabricated in case they are lost or damaged. However, some advertised advantages still have to be proven with further research needed. Articulation and intra-oral scanning are areas that still need development.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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