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Digital Removable Complete Denture—an Overview

Carlo P. Marinello[1] · Rudolf Brugger[2]

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Abstract

Purpose of Review During the last few years, the interest in fabrication of computer-engineered removable complete dentures has grown intensively. Innovative clinical and technological advances are driving forces. They allow (i) the creation of new and more efficient workflows, (ii) an emergence of modified and easier procedures, and (iii) the use of alternative biomaterials with improved properties. The results are a better fit and retention of the digital complete dentures, as well as a generally high satisfaction of patient and clinician, while reducing the number of appointments and the technical input. The purpose of this narrative review is to present the historical, clinical, and technological developments in the field of digital removable complete dentures and to evaluate the future potential of this technology.

Recent Findings The fabrication of a digital complete denture either by milling separately the base and the denture teeth set-up or by milling a monolithic denture is well investigated. Concurrently the trend for fabricating complete denture bases by using the 3D print technology is growing. There is plenty of research showing that milling dentures from standardized pre-polymerized polymethyl methacrylate pucks guarantee the fabrication of homogenous objects with excellent biomaterial properties. The results indicate a better base adaptation, a higher flexural strength, an improved resistance to denture staining, and no polymerization distortion while milling. Furthermore, a sophisticated milling strategy allows to obtain a detailed and accurate intaglio and cameo surface, which is even exceeded when 3D printing. The clinical and technological freedom, to either combine selectively analog and digital steps or to take a totally digital workflow ending with milling or 3D printing, opens countless opportunities in the field of removable complete dentures. Whatever steps are taken, whatever sophisticated technology is chosen, still only the professional and individual know-how of the dentist in combination with the manual skills and the experience of the dental technologist—including especially the finish of the final product—will lead to a superior teamwork result. Limitations inherent to the milling process are the waste of raw material, the wear of milling tools, and the challenge to access undercut areas; the reasons are the milling bur size, the number of milling axes, and the limited movements of the machining axes. The advantages of additive manufacturing lay in a high resolution of complex geometries and a reduced waste of the biomaterial. As a limitation, the accuracy of the object, i.e. deformation, may be affected by several fabrication parameters, such as the polymerization light intensity, the build direction and angle, the layer thickness and numbers, the amount of supporting structures, and the post-processing procedures. However, with improved materials and techniques, printing may also become a primary method for fabricating digital complete dentures.

Summary The available clinical and technical information and multiple research demonstrate that the integration of digital steps into the workflow for fabricating removable complete dentures opens countless options, leading to the achievement of an esthetically, functionally, biologically, and technically high-quality end product. However, a longer learning curve must be considered. To simplify the fabrication methods of complete dentures in specific clinical situations, with the aim to increase efficiency and to save resources, is indicated. However, the use of conventional step-by-step approaches may still be valid for complex clinical situations. It is foreseeable that for treating edentulous patients, the evolution of new biomaterials, the introduction of sophisticated digital methods, and the development of improved software will follow attractive workflows with more standardized, easier, achievable, and predictable results. It challenges the clinician to have a more direct impact on denture construction and to provide the patient with the opportunity to participate in the esthetic designing. A generally higher efficiency and satisfaction for all partners involved in the fabrication process of removable complete dentures—patient,

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dental technologist, and dentist/prosthodontist—is the result. For a dental technologist, it is a great challenge to set up esthetic and functional denture teeth in an edentulous 3D space defined by the maxilla, the mandible, and the oral soft tissues. It is a question of time and partly already existing that machine learning—a branch of artificial intelligence—has the capacity to recognize specific intramaxillary and intermaxillary situations and to deliver an acceptable functional and esthetic denture teeth set-up, at least as a working base. Furthermore, with the introduction of a face scanner, the patient becomes virtually present anytime. Transferring the virtual situation in a physical articulator makes judgments and changes possible in both worlds simultaneously. Innovations such as robot technology still are in their infancy; however, there are aspirations to automatically place denture teeth into a dental arch. There is a great responsibility for a dentist and a dental technologist for fabricating high-quality removable complete dentures. Factors, such as a meticulous diagnosis and treatment planning, a personal communication between the involved persons, and a profound knowledge of the clinical and technical possibilities, should lead to an easy, simple, cost-effective, and highly satisfying denture fabrication workflow. The digitalization in this field already has and will even more activate research and clinical opportunities in the near future. The globally existing many edentulous patients will highly appreciate the excellent results.

Keywords CAD-CAM (computer-aided design-computer-aided manufacturing) · Conventional removable complete denture · Digital denture (computer-engineered (removable) complete denture) · Additive manufacturing (3D printing, rapid prototyping) · Subtractive manufacturing (milling)

Introduction

General Situation

In an age of successful use of dental implants, the question is opportune, if the treatment of an edentulous patient with removable complete dentures is still important and indicated? Despite a potential disagreement among many clinicians, the answer is *yes*. Regarding the global economic situation, for most edentulous patients, the delivery of complete dentures remains a desirable treatment. However, the following aspects have to be considered from the clinician's point of view [107]: (i) For many dentists, the treatment of an edentulous patient with conventional dentures is not attractive, (ii) the continuing education in this field is minimal or hardly existing, (iii) the conventional clinical and technical workflow to fabricate complete dentures is rather laborious, (iv) many of the relevant procedural steps depend on the (artistic) experience of the dentist and of the dental technologist and therefore rely on a weak scientific evidence, (v) anatomically challenging cases are difficult to treat successfully, (vi) there is a risk for an unpredictable denture acceptance by the patient, and (vii) in certain cases, the cost-income ratio may not make any financial sense. Nevertheless, it is just the treatment of edentulous patients that asks for (i) a meticulous dental history, (ii) a systematic diagnosis and treatment planning, and (iii) a profound understanding of the clinical procedures, including the communication with the patient respecting his individual personality and with the dental technologist respecting his technological knowledge and potential. This is what makes the comprehensive rehabilitation of an edentulous patient most challenging. The complex combination of these factors contributes to the reluctance of certain dentists to provide removable complete dentures, despite the indisputable global demand by many patients.

Although dentists may offer to an edentulous patient in the first place an implant therapy, there are reasons to refuse this type of treatment by the patient: anxiety about surgery, fear of pain, costs, and treatment time. Furthermore, from a general health point of view, patients may not be candidates per se for implants: uncontrolled diabetes, immune deficiency issues, history of intravenous bisphosphonate treatment, heavy smoking habits, alcohol abuse, psychology, and dementia [1]. In such cases, professionally fabricated and well-maintained removable complete dentures still represent a treatment of choice. Here is exactly where the potential of offering digital dentures may lie.

Whereas with a maxillary complete denture, the expectations of patients can mostly be met, problems with mandibular complete dentures may include lack of stability and retention, as well as soreness and pain [2]. In such cases—especially in maladaptive patients—the use of dental implants—for a removable or a fixed superstructure—may lead undisputedly to a higher improvement in oral function and quality of life [3].

Tooth loss as a consequence of caries, periodontitis, trauma, or iatrogenic factors contributes to a compromised orofacial system. Corresponding to Gupta et al., tooth loss is associated with an increased risk of early mortality; also, the prosthetic care of edentulous patients improves quality of life and reduces morbidity. The rehabilitation of an edentulous patient with complete dentures restores only to a certain point the loss of tissue, esthetics, function, phonetics, and patient satisfaction. Therefore, treating edentulous patients with removable complete dentures remains a compromise and a demanding task [4]. Furthermore, in most cases, the creation of a good relationship with a patient is more important than a technically perfect denture for achieving patient satisfaction. Also, technically perfect complete dentures do not per se change the dietary selection nor improve the quality of diet in edentulous patients [5].

Epidemiology of Edentulism and Longevity of Complete Dentures

Edentulism describes the endpoint of chronic oral diseases. The incidence of total tooth loss has continuously decreased in high-income countries [6]. Despite this decrease, an age-related and social gradient exists, with the highest prevalence in the elderly and in the socioeconomically disadvantaged groups [7]. Reductions in the prevalence of edentulism are expected to be offset by the projected increase in the number and proportion of elderly people in the future [6]. Edentulism therefore likely remains a significant health condition requiring prosthetic rehabilitation [8].

Evidence regarding the longevity of complete dentures is limited. A recent systematic review found a denture replacement period of about 10 years, in which the longevity of maxillary dentures was greater than that of mandibular dentures [9]. The authors claim to educate patients to seek regular maintenance for their dentures as well as for their oral mucosal health.

Challenges of Treatment with Complete Dentures

The conventional workflow for fabrication of complete dentures is elaborate and requires considerable time and experience in the clinic and especially in the dental laboratory. It normally takes 4–5 sessions (Table 1): (i) a primary impression with a prefabricated impression tray or with the existing denture, (ii) a final impression with a customized impression tray, (iii) a determination of the vertical and horizontal dimension, (iv) a functional and esthetic try-in of the denture teeth, and (v) a delivery and incorporation of the complete dentures. Furthermore, the post-insertion workload for maintenance and repair of the dentures must be considered [10]. These sessions are accompanied by a subtle and laborious handicraft in the laboratory.

A simplification of the treatment is desirable by combining some clinical and laboratory steps and by saving time and possibly costs for dentist, technologist, and patient. Concurrently, the quality of the dentures and patient satisfaction can be improved (i) by adding standardized and more predictable steps, (ii) by using an innovative and supporting CAD-CAM software, and (iii) by processing in a standardized form industrially pre-manufactured biomaterials. Systematic reviews confirm that a conventional step-by-step complete denture fabrication procedure does not produce per se better clinical results than the use of a simplified method in terms of general satisfaction, the OHIP-Edentulous scale, denture quality, and mastication ability [11, 12].

The often reduced neuroplasticity and stereognostic abilities of elderly edentulous patients may provoke adaptation problems to new complete dentures [13]. In such cases, digitally fabricated duplicate new dentures may be an adequate and efficient solution [14–16]. They allow the processing of a high-quality biomaterial and a better adaptation of the intaglio fit, while copying the functional areas of the cameo surface of the existing dentures. Furthermore, the digital data of the denture—in case of loss, fracture, or reworking—remain available to replicate the affected dentures. This may be particularly important for the frail elderly in long-term care facilities. In such cases, additionally the potential microbiological burden (e.g., risk for aspiration pneumonia, adherence of candida) from the removable dentures must be considered [17–19]. From a biological point of view, easy cleansable complete dentures with a high-quality surface (no porosities, easy polishable)—facilitating denture hygiene—could potentially have a relevant preventive effect on mortality from pneumonia in hospitalized elderly people and elderly nursing home residents [20].

Aim

The purpose of this narrative review is to present the historical, clinical, and technological developments in the field of digital removable complete dentures and to evaluate the potential of this technology.

Digital Complete Denture

Definition and History

According to the Glossary of Digital Terms, a digital denture is a complete denture created by or through automation using CAD (computer-aided designing), CAM (computer-aided manufacturing), and CAE (computer-aided engineering) in lieu of traditional processes. A digital denture is achieved when the final shape of the denture is manufactured through automation to ensure there are no conventional errors from pouring, investment casting, or injecting the material as done in traditional denture fabrication [21].

CAD-CAM has become an indispensable part of dentistry in general and of prosthodontics in particular. The idea of successfully digitizing the workflow for fabrication of complete dentures was considered for a long time as rather improbable [22, 23]. It was felt that the necessary comprehensive application of individual clinical and technical rules, as well as of the essential clinical experiences of dentist and dental technologist, may be obstacles. Although

Table 1 Overview of commercially available CAD-CAM-based manufacturers of complete dentures

Clinical	Conventional workflow	Avadent * 2-session workflow	Baltic **	Dentca ***	Ivoclar **** 3 or 4-session workflow
1st session	Primary impression (for fabrication of customized impression trays)	Final impression	Final impression with trays with teeth (upper and lower KEY, 3 sizes)	Specific impression trays (underextended at the borders allowing to take functional final impressions)	Primary impression (Accudent®)
		Determination of vertical and horizontal dimension	Determination of vertical and horizontal dimension (specific facebow)	Determination of vertical and horizontal dimension (Gothic arch tracing)	Primary determination of vertical and horizontal dimension (Centric Tray)
		Determination of esthetic/functional aspects		Lip ruler for upper lip length and incisal edge position	Determination of occlusal plane (UTS CAD)
		Try-in on special demand		Try-in on special demand	Papillameter (Candulor) upper lip length + lip closure line
2nd session	Final impression (for fabrication of a base with a occlusal rim)	Incorporation (verification of fit, of functional morphology, of cameo surface, of occlusion)	Incorporation (verification of fit, of functional morphology, of cameo surface, of occlusion)	Incorporation (verification of fit, of functional morphology, of cameo surface, of occlusion)	Final impressions with milled customized trays
					Determination of vertical and horizontal dimension (Gnathometer CAD; Gothic arch tracing)
3rd session	Determination of vertical and horizontal dimension (facebow registration)				Try-in of milled monolithic trial dentures (Ivobase CAD + individual manufactured or milled denture teeth)
					Checking esthetic + functional (phonetic, occlusion, retention, etc.) aspects
4th session	Try-in Checking esthetic + functional (phonetic, occlusion, retention, etc.) aspects				Incorporation (verification of fit, of functional morphology, of cameo surface, of occlusion)
5th session	Incorporation (verification of fit, of functional morphology, of cameo surface, of occlusion)				
Denture manufacturing protocol	Compression/injection molding	Milling/printing	Milled prefabricated base with denture teeth	Printed base with recesses for denture teeth	Milled base with recesses for denture teeth
	Milling/printing				
Maintenance	Denture hygiene	Denture hygiene	Denture hygiene	Denture hygiene	Denture hygiene
	Oral mucosal health	Oral mucosal health	Oral mucosal health	Oral mucosal health	Oral mucosal health

Other systems: ceramill® fds (wax) (Amann Girrbach, A-Koblach); Lucitone Digital Print and IPN 3D Carbon Print (DentsplySirona, York, PA, USA); Vita Vionic Solutions® (VITA Zahnfabrik, D-Bad, Säckingen); 3-shape Digital Dentures (3-shape A/S, Holmens Kanal 7, DK, Copenhagen); Digital Denture (Zirkonzahn GmbH, An der Ahr 7, 39,030, I-Gais, BZ)

*Avadent®, AvaDent Digital Dental Solutions, Scottsdale, AZ, USA

**Baltic Denture System, Merz Dental GmbH, Lütjenburg, Germany

***DENTCA™ CAD/CAM Denture, Torrance, CA, USA

****Digital Denture, Ivoclar Vivadent AG, Schaan, Liechtenstein the conventional workflow to fabricate complete dentures is well established and successful, factors such as standardization and simplification accelerated the interest in CAD-CAM technology for removable prosthodontics.

Historically, the first attempt to fabricate complete dentures by CAD-CAM was made using a prototype system (i) taking a conventional impression with a special double tray, (ii) connecting the trays at the determined horizontal and vertical dimension, (iii) scanning the trays with a 3D laser scanner, (iv) using rapid prototyping (3D laser lithography) for fabricating the two outer shells (intaglio and cameo surface), and (v) filling the inside with tissue-colored auto-polymerizing resin composite [24]. Later, the duplication of complete dentures (laser scanning of intaglio and cameo surfaces) using CAD-CAM technology with a CNC (computerized numerical control) processor for cutting modeling wax was described [25]. Then, a digital denture teeth arrangement was proposed by a special software using anatomic measurements; the scanning of the edentulous casts was performed by different types of scanners [26]. Another report used a 3D laser scanner and developed CAD software and rapid prototyping technology to make individualized physical flasks for complete dentures; however, conventional laboratory procedures and classic denture materials were still used to finish the dentures [27]. More recently, the fabrication of a complete denture by CBCT scanning of patient's dentures or of wax trial dentures and processing the STL data to reproduce a new denture base—either by milling or by rapid prototyping—was presented [28, 29]. Finally, a special clinical impression procedure was described to get the morphology of the denture bases (intaglio and cameo surface as well as the muscular and phonetic positions for the placement of the denture teeth the recorded information was scanned and the complete denture bases were virtually designed and milled from resin. A prototype 3D tooth arrangement program was used to virtually place the denture teeth, which were manually bonded into recesses of the base [23].

Commercially Available Systems, Workflows, and Classification

Early, two commercial CAD-CAM-based manufacturers of complete dentures found entrance into the market: Avadent Digital Dental Solutions (Global Dental Science, Scottsdale, AZ) and Dentca CAD-CAM Dentures (Dentca, Torrance, CA) (Table 1) [30–33].

The workflow of a representative system (Avadent Digital Dental Solutions), offering either a milled (or printed) denture base with bonded teeth (prefabricated or milled) or a monolithic prosthesis, is presented (Avadent Clinical Protocols). For the original 2-session workflow, existing dentures in an acceptable state (fit, course of occlusal plane and dental arch, esthetics, vertical and horizontal dimension of occlusion) are beneficial. The first session serves to acquire the minimally necessary clinical information such as the following:

1. Impressions of the edentulous ridges (analog with existing denture or with a commercially available impression tray). Basically, an adhesive is applied, and border molding is carried out with a regular-body PVS impression material and followed by a thin layer of light-body PVS impression material;
2. Determination of the horizontal and vertical dimension (either using the existing dentures, or specific trays (Avadent-Wagner EZ guide) or using the proprietary anatomical measuring device (AMD));
3. Determination of the esthetic and functional aspects (upper lip support, prosthetic tooth mold selection, determination of the position of the midline, of the central incisal edge and of the canine).

All this information—preferentially supplemented by photographs of the patient—is sent to the dental laboratory, where the denture base and the desired denture teeth arrangement are virtually established and then approved by the clinician. In a second appointment, the complete dentures are inserted.

In the near past, numerous clinical protocols to achieve the necessary clinical information have been described, whereby the 3-session workflow has gained most clinical acceptance [34]. Hereby, the second session serves to check a try-in of a milled or printed trial denture or a milled or printed base with denture teeth set-up in wax.

In the cases, where (i) the patient does not have dentures, or (ii) the information of the existing dentures is insufficient, or (iii) the new dentures require significant changes from the previous dentures or (iv) it is a complex case, it is strongly recommended to lean on a more traditional step-by-step denture fabrication technique.

Digital denture systems are classified either according to their fabrication process (subtractive/milling; additive/printing) or according to their workflow concept (number of sessions) [35]. There are numerous options to combine analog and digital steps and to combine the fabrication of the base with the one of the denture teeth (Tables 1 and 2).

Applications, Advantages, Potential, and Limitations

Generally computer-engineered complete dentures are indicated as a definitive single complete denture, maxillary and mandibular complete dentures, immediate denture, provisional denture, duplicate denture, for a diagnostic evaluation

Table 2 Fabrication concepts for digital complete dentures

MILLED Denture Base	DENTURE TEETH either bonded in milled recesses of the denture base or on milled abutments	PRINTED Denture Base
+ Milled Denture Teeth Set	Hybrid combination of milling and printing	+ Milled Denture Teeth Set
+ Milled individual Denture Teeth		Printed Denture Base + Milled individual Denture Teeth
+ Prefabricated Denture Teeth		Printed Denture Base + Prefabricated Denture Teeth
Monolithic Denture Base with Denture Teeth		Printed Denture Base + Printed Denture Teeth Set [indiv]

of a denture tooth set-up in fixed and removable implant cases as well as for fabricating a radiographic or surgical template that includes the placing of implants [36].

Advantages for the Dentist, Dental Technologist, and Patient

1. Clinical data are recorded in fewer appointments, reducing clinical chair time and—in selected cases—the costs, leading to a higher patient satisfaction [37–41]. As a side effect, there may be a greater likelihood of the patient to return to the same dentist who has the documentation of all the past data.
2. Thanks to the clinical digital data and the software in the dental laboratory, technological steps are accomplished in a shorter time, leading to a more standardized high-quality end product [42]. For the dental technologist, the design of a complete denture is shifted from a manual wax-up and denture teeth set-up to a digital design on a screen, and the fabrication of a complete denture from a manual to a digitally guided fabrication. Both are in a more standardized, controlled, easy, fast, and predictable way.
3. The repository of digital data allows any time the fabrication of a spare or replacement denture, the fabrication of a new denture as a copy (duplicate) of the old denture, and an easy rebasing by producing a "new old" denture [14–16].
4. In edentulous patients who are in need of implants, the data may be used for a complete digital workflow by designing and fabricating a diagnostic denture teeth set-up, a provisional denture, a radiographic or surgical template that supports the planning and the placing of implants, and, not least, the fabrication of a final restoration [43].

Technical Properties

Milling a pre-polymerized puck of polymethyl methacrylate (PMMA) that is dimensionally stable guarantees several improvements of the biomaterial properties compared to conventional heat-polymerized PMMA [35, 45, 48].

1. A higher flexural strength, fracture toughness, and modulus of elasticity [44–49], allowing in the indicated case the fabrication of a thinner denture base.
2. A higher surface hardness [50], leading to a less vulnerable surface.
3. Better surface properties (smoother surface texture, more hydrophilic, better wettability), depending on the quality of the milling path and on the milling tools used, which might make CAD-CAM denture surfaces less attractive to microbial colonization [46, 49, 51, 49, 51]. After polishing, milled specimens showed superior surface characteristics than 3D printed and conventionally produced specimens [52]. This corresponds to the clinical observation of less plaque and calculus deposition as well as of an easier cleansibility of the dentures [45]. The smoother surface texture together with a higher biomaterial density with less porosities [53] may lead to a better color stability and a decreased susceptibility to surface staining [54]. Al-Qarni et al. reported that all evaluated acrylic resin specimens (Lucitone 199 (compression-molded), Dentsply Sirona; IvoBase Hybrid (injection-molded), Ivoclar Vivadent AG; Lucitone 199 (milled), AvaDent, Global Dental Science LLC) had significant color change after immersion in coffee or red wine at the tooth-denture base interface. In contrast, CAD-CAM milled specimens were less likely to harbor stains than conventionally fabricated specimens.
4. A reduced monomer content for industrially produced PMMA pucks [53], and a similar monomer release of CAD-CAM dentures compared to heat-polymerized dentures [33]. However, the influence of the bonding agent to fix the denture teeth plus the thickness of the pre-polymerized puck that hinders the evaporation of the monomer from the inner core of the puck was obviously not taken into consideration.
5. A better denture base adaptation and reproducibility was detected (superimposition of STL files) for CAD-CAM milled dentures compared to conventional (pack and

press, pour, injection) fabrication techniques [55, 56]. In contrast, McLaughlin et al. found that CAD-CAM and injection molding produced equally well-fitting dentures. A higher overall accuracy of the denture base for the milled, over the 3D printed, and over the conventionally fabricated denture base for both maxillary and mandibular arches was recently reported [57]. These trends were confirmed by several studies, in which milled bases showed better trueness than printed bases [44, 48, 49, 58–61]. A recent systematic review summarized that no clear conclusions can be drawn about the superiority of CAD-CAM milling and 3D printing regarding denture accuracy [62]. A reason for the contradictory results mainly lies in the heterogenous experimental set-ups. A multi-center analysis of try-in dentures comparing the accuracy of 3D printing with milling concluded that—although milling remains the benchmark technique for accuracy—the overall performance of 3D printing was within a clinically acceptable range [63, 64].

6. A lower degree of fine reproducibility was reported in the milling or printing method compared to the injection molding method [65].
7. An optimal combination of accuracy and reproducibility was produced by the CAD-CAM milled monolithic technique. This was tested through denture tooth movement, after checking several fabrication techniques (compression molding, fluid resin, injection molding, CAD-CAM bonded, and CAD-CAM monolithic; [66, 67].

Clinical Properties

1. A similar biocompatibility between a CAD-CAM PMMA and a conventionally heat-polymerized PMMA was found in vitro in a cell culture (human osteoblasts, mouse fibroblasts; [68].
2. A better denture retention mainly due to the absence of polymerization shrinkage was observed for milled dentures compared to conventional dentures [69]. The retention was measured in vivo with a custom-milled device allowing a vertical dislodgement force to the denture. Using the same measuring device, the application of a denture adhesive leads to a reduced retention for the milled bases,most probably the denture adhesive does not allow a perfect reposition of the denture anymore [70].
3. A reduced affinity for adhesion of *Candida albicans* on a CAD-CAM denture base than to a conventional base (which also had a greater surface roughness) was reported by Al-Fouzan et al. As a consequence, a decrease of the incidence of denture stomatitis is postulated.

With all new technologies, limitations have to be considered. There is a learning curve for both the clinician and the dental technologist. The personal prosthetic experience coming from a conventional workflow and the patient selection plays an important role. The assessment of 3D digital data on a screen instead on an analog model is more challenging and may lead to misinterpretations [71]. A teamwork-oriented good communication between clinician and dental technologist is therefore crucial. Certain clinical and technical steps are still considered a compromise (e.g., bonding of denture teeth). Clinical studies point out that patient dissatisfaction, inadequate retention, and esthetic complaints—if they occurred at all—were mostly related to the lack of a denture try-in [72]. Most limitations can be managed by meticulously choosing a patient-adequate workflow.

Clinical Aspects

Workflows

Numerous workflows for fabricating computer-engineered removable complete dentures have been presented [79−84, 102, 103, Figs. 1 and 2]. Most protocols use combined analog and digital clinical steps. The analog steps are then secondarily digitized or are used as a physical inspection (clinical try-in). Completely digital clinical workflows are available; however, most of them represent a proof of concept or are in need for a sophisticated management of an intraoral scanner as well as the software in the dental laboratory [64, 66, 67, 73]. In cases where a significant individualization of the denture base and/or denture teeth set-up is necessary, the manual dexterity and artistic experience of the dental technologist is still required.

Long-term Behavior, Clinical Outcomes, and Costs

Kattadiyil et al. compared clinical treatment outcomes between conventionally and digitally processed removable complete dental prostheses (AvaDent Clinical Denture). Patients reported in general higher satisfaction scores, higher preference, better retention, and less time needed for fabrication of the digital dentures. In a prospective 1-year follow-up cohort study, Bidra et al. evaluated monolithic CAD-CAM dentures (AvaDent Clinical Denture; 2-visit protocol). Since the ratings for overall satisfaction and assessment were good, but better in patients than in clinicians, the 2-visit protocol was considered a viable option for edentulous patients. The need for careful patient selection and for additional time for guiding the fabrication process is emphasized; also, the use of a trial denture—-leading to a third visit—is recommended.

In a cross-sectional and in a retrospective survey, Saponaro et al. concluded that if a 2-visit protocol (AvaDent

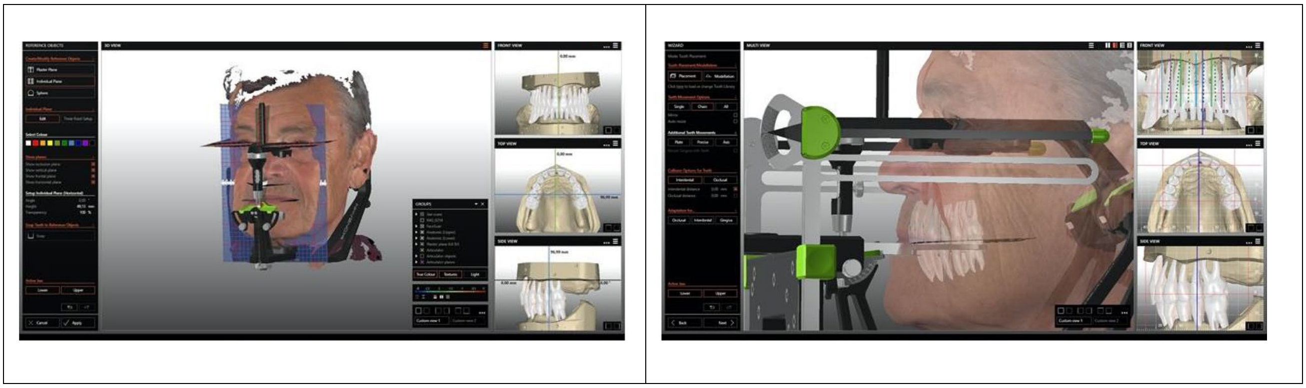

Fig. 1 When all the necessary information from an edentulous patient is acquired (face scans, scans of edentulous jaws, plane positioner, plane finder, digital photographs, dental casts, and CBCT data), the different parts are superimposed, aligned, and matched leading to a virtual patient, who is anytime available. Denture teeth are selected from the library and placed on the virtually surveyed casts. A virtual articulator accompanies all the design steps. Denture teeth with anatomic roots allow a better evaluation of tooth axis and an individual forming of the thickness and the course of the "prosthetic gingiva" (kindly provided by Zirkonzahn GmbH, I-Gais)

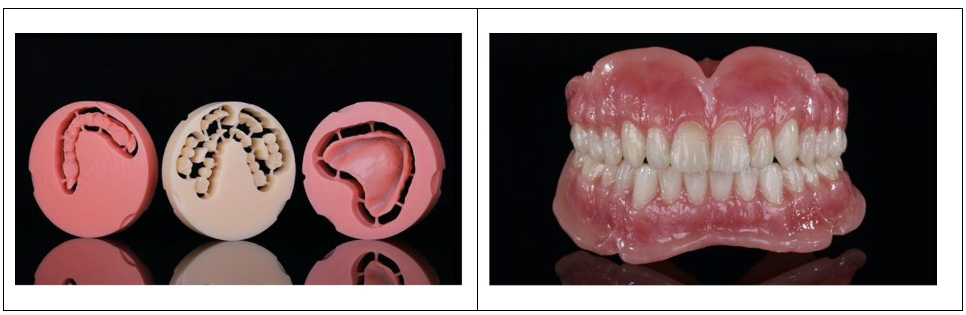

Fig. 2 Normally the denture base and the denture teeth are milled separately. The denture teeth are bonded either in milled recesses of the denture base or on milled tooth abutments. The fabrication of a monolithic prosthesis (milled or printed) is possible and mostly indicated for a try-in denture for verification of retention, occlusion, and esthetics. The computer-engineered removable complete denture is ready to be delivered. An esthetic finish has been performed. Remarkable are the milled denture teeth with an inherent dentin color gradient and the outline of the "prosthetic gingiva" (kindly provided by Zirkonzahn GmbH, I-Gais)

Clinical Denture) is successful, it should also be cost-effective. The effective mean number of appointments needed to insert the denture was 2.39; complications reported were lack of retention, inaccurate occlusal vertical dimension, and incorrect centric relation. It was concluded that CAD-CAM fabricated complete dentures are a viable treatment option for carefully selected patients. The questionnaire-driven information of the patient's ratings of their previous conventional dentures and their CAD-CAM dentures resulted in 70% judging the latter as better.

Schlenz et al. analyzed retrospectively the performance of digital complete dentures (Digital Denture, Ivoclar Vivadent). They showed "an acceptable clinical performance" in terms of survival and maintenance. The main reasons for interventions were removal of pressure spots and surprisingly a relining of the denture.

Patients, who had received either CAD-CAM (Avadent Digital Dental Solutions 2-appointment protocol and Wieland Digital Denture System 4-appointment protocol) or conventional (5-appointment protocol) removable complete dentures, were compared retrospectively regarding treatment duration, clinical and follow-up visits, adjustments, and maintenance requirements. Both types of dentures required a similar number of treatment adjustments; however, CAD-CAM was less expensive regarding the overall costs and laboratory costs and leads to fewer clinical visits [37].

Peroz et al. reported that conventional complete dentures needed more time for clinical visits and technical fabrication than digital dentures (Baltic Denture System), but digital dentures caused more transient physical pain because of sore spots. In contrast, Clark et al. observed fewer appointments from start to finish and postoperatively for digital compared to conventional dentures. Srinivasan et al. found that the digital denture protocol is less costly than the conventional complete denture protocol. The costs for clinical chairside time, laboratory, and the overall costs were significantly lower, although the material costs were higher. Therefore, the digital denture protocol might be highly beneficial for the elderly and/or the compromised edentulous patient. Smith et al. reported that digital technology created a cost-saving benefit, fewer visits to complete the denture fabrication steps, and fewer post-insertion visits leading to further savings. The patient and dentist satisfaction was consistently high.

Impression Taking, Determination of Vertical and Horizontal Dimension, and Try-in

The aim of impression taking of an edentulous jaw is to reproduce the mucosal denture bearing area—a viscoelastic soft tissue—in a healthy state without pressure, and to ensure a perfect inner and outer peripheral seal at the denture border area, leading as a consequence to support, stability, and retention of the denture base [74]. There is a high variety of the materials and techniques used, and there are individual preferences for the selected workflows [75–77]. Although certain clinical situations may justify a multiple-step-impression procedure, it was demonstrated that a 2-step procedure is not per se better—in terms of technical quality of the denture—than a 1-step technique [78, 79]. The clinician therefore chooses an impression procedure that easily and comfortably fulfills the demands of a perfect impression [80]. Subsequently, with the help of a laboratory desktop scanner, the conventional impression is converted into a virtual edentulous cast. The use of an intraoral scanner for directly digitizing the denture bearing area is another option [66, 67, 77, 81, 81–85, 85, 86, 86b)]. Although the results seem to be promising, there are certain compromises and limitations [87]. Intraoral scanners have an accuracy similar to that of conventional impression methods; however, the scanning protocol used influences strongly the final result. According to Lo Russo et al., intraoral scanners take a mucostatic impression of the edentulous arch. They cannot yet replicate functional movements. This is not regarded as a disadvantage, because it is assumed that retention is mainly achieved by an intimate contact of the denture base with the underlying tissues. The authors accept therefore the limitations of (i) shorter denture flanges, (ii) a possibly reduced retention and stability, (iii) an impaired lip and cheek support, and (iv) a compromised internal peripheral seal. This concept however will have to be proved in further clinical studies. There are attempts to combine intraoral scans with digital relining procedures, aiming at fabricating a complete denture with functional borders in a fully digital workflow [88]. The combination of a conventional impression with an intraoral scan has been described for pressureless impression taking of flabby tissue [77]. Hereby, the flabby tissue is scanned through a window in the impression tray, whereas the stable tissues are replicated by a conventional impression. The two impression datasets are then superimposed.

A conventional impression using a custom tray in combination with an elastomeric impression material is still a method of choice. The result is then digitized in the dental laboratory. The challenges for direct intraoral scanning of edentulous jaws—especially in the mandible—are related to factors such as the mobile soft tissue, the smooth mucosal surface texture covered by saliva, the formation of a saliva lake, the movements of the tongue and cheeks, the management of frenula, and the lack of stable references. Nevertheless, in selected cases, intraoral scanning of edentulous jaws is possible [81, 85, 86] and b). In a direct comparison of 3 impression taking methods, a conventional open-mouth impression method, a simple modified closed-mouth impression method with a novel tray, and a digital impression method using an intraoral scanner, there was no difference between open-mouth and closed-mouth method for completely edentulous patients and there was no difference in the replication of the supporting areas between the digital and the conventional impression method [89].

After having taken final impressions, the conventional workflow foresees the fabrication of record bases with occlusion rims in wax. This allows a step-by-step determination of the vertical and horizontal dimension [80]. For efficiency, the latter can be performed at the day of impression taking [74, 80, 99, 107, 109]. Fang et al. report about an individually fabricated appliance to combine a custom impression tray with an intraoral Gothic arch, producing definitive impressions and recording centric relation in a single step.

Today's technologies get precise 3D models of edentulous jaws in the exact position to each other. This permits with the help of a sophisticated dental laboratory CAD-CAM software to get an adequate denture teeth arrangement on a defined extended base. At this moment, the necessity for a prototype denture for a denture teeth try-in is evaluated (monolithic, milled, or print) or the final denture is directly fabricated (Table 2).

Denture Delivery, Maintenance, and Denture Hygiene

At the time of delivery of the removable complete denture, the following aspects are checked with the help of a spot indicator paste: (i) the extension of the denture flanges, (ii) the lip and cheek support, (iii) the internal peripheral seal, (iv) the presence of pressure spots, and (v) with an articulating paper the occlusion in static and dynamic. The patient is informed about (i) the necessity of regular visits (once per year) for soft tissue examination, (ii) the importance of denture hygiene, and (iii) the professional cleaning and polishing of the dentures [9, 90].

A recent systematic review reinforces established claims that—irrespective if a denture is worn at night or whether it is dry stored—a daily meticulous mechanical denture hygiene just using liquid soap and a soft brush is most important before going to sleep. Also, the weekly use of an alkaline peroxide-based cleaning tablet to reduce the amount of *Candida albicans* and to prevent the development of denture stomatitis is recommended [91].

A report on post-insertion visits for denture adjustments for patients treated with conventionally fabricated dentures versus milled dentures showed no differences between the two groups [92]. The overall number of denture adjustments was lower than in the study of Bidra et al. for CAD-CAM dentures over a 1-year follow-up period.

Technical Aspects

Fabrication Mode (Subtractive, Additive)

Conventionally fabricated removable complete dentures (compression molding, injection molding) show material-inherent and process-inherent dimensional changes (polymerization shrinkage, thermal contraction and expansion; [53]. These changes may affect the accuracy of the denture base and the occlusion (preliminary contacts, change of vertical dimension of occlusion, [66, 67, 80]. In contrast, CAD-CAM fabricated denture bases exhibit fewer dimensional changes [56]. Hereby, either an established subtractive milling or an additive rapid prototyping (3D printing) CAD-CAM process is available. Milled complete dentures are used as final restorations, whereas the printed dentures at the moment are mainly indicated for trial or provisional dentures [93].

Milling from standardized pre-polymerized PMMA pucks leads to the fabrication of homogenous objects with excellent biomaterial properties. Furthermore, a sophisticated milling strategy allows to obtain a detailed and accurate intaglio and cameo surface. There are clinical and technical experiences since almost 10 years. In in vitro direct comparisons of milled versus rapidly prototyped complete dentures, the former was superior in terms of trueness of the intaglio surfaces [59, 94].

Additive manufacturing offers the benefits of short manufacturing times, reduced numbers of appointments, a high-resolution printing of complex geometries, a fine detail reproduction, and a reduced waste of material [95, 96]. Printing parameters, such as laser intensity, calibration of printer and software, resin properties, build direction and angle, layer thickness and numbers, bond between the layers, amount of supporting structures, and post-polymerization conditions, play an important role regarding the quality of the end product [97]. In printed dentures, non-polymerized photosensitive liquid resin can potentially cause a negative mucosa (patient) and/or skin (technologist) reaction. A recent review reports on the recommended usages for 3D printed complete dentures: interim or immediate dentures, custom trays, or record base fabrication for conventional workflows. More well-designed clinical studies are needed to prove the claimed advantages of additive manufacturing [93].

Artificial Intelligence and Robotics

Artificial intelligence is a technology that integrates machines to mimic intelligent human behavior and robots will have a larger impact on the way we diagnose, plan, and treat edentulous patients in the future. Compared to other medical fields, robot technology in dentistry/prosthodontics still lies in a relative infancy [98]. A process of an automatic set-up of denture teeth into a dental arch for fabricating complete dentures with the arch size as a reference has been described [99]. Also, an "intelligent dental robot" was fabricated to replicate human's masticatory movements and perform stress and wear test on artificial dentures [100]. As soon as the software for fabricating complete dentures will be more developed and will rely on more clinical-anatomic and technical data, a continuous automation of the many necessary single steps to design a complete denture can be expected [101].

Conclusions and Future Aspects

There is a great responsibility for a dentist and a dental technologist to fabricate high-quality removable complete dentures. Factors, such as a meticulous diagnosis and treatment planning, a personal communication between the involved persons, and a profound knowledge of the clinical and technical possibilities, should lead to an easy, simple, cost-effective, and highly satisfying denture fabrication workflow. The digitalization in this field already has and will even more activate research and clinical opportunities in the near future. The globally many edentulous patients will highly appreciate the results.

Already today and in the future even more, digital data facilitate the workflow for treatment of edentulous jaws. A virtual patient is obtained by a superimposition of intraoral scans, of digital photographs, of dental casts, and of CBCT data with facial scans. This offers a permanent 3D visualization of the patient and a location-independent communication between the dentist and dental technologist. Also, the integration of a reference plane, to which the occlusal plane is aligned, allows to check and modify the esthetic appearance as well as the functional demands [102] and [103]. The simulation of treatment steps and of possible end results represents a modern way of communication and education between the dentist, dental technologist, and patient. The freedom to choose between different denture fabrication procedures (milling and printing, base and denture teeth separate or monolithic, switching between the analog and virtual world, fabrication of a trial denture, yes or no) gives a wide range of individual opportunities and guarantees an extremely exciting future in the field of removable complete dentures. By the constantly improving software, dentists and dental technologists gain a better planning security, a higher processing quality, and a better predictability.

Denture bases are mostly fabricated with PMMA. Although their physical properties and surface quality are improved through milling and printing compared to i. e. injection molding, they still remain highly susceptible to biofilm formation (bacteria, fungi). Techniques to incorporate biodegradable microcapsules or nanocarriers containing organic antimicrobial agents into the denture base or a modification via polymeric surface coating become challenging research directions [104, 105]. Especially the frail geriatric and the immunosuppressed edentulous population could profit from an inherent pharmaceutical activity of a denture base. Not least, it is speculated that functional dentures may have a potential beneficial effect on the cognitive status of an edentulous person via the mastication pathway [106].

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Declarations

Conflict of Interest Dr. Carlo Marinello and CDT Rudolf Brugger report personal fees from Zirkonzahn GmbH, I-Gais, outside the submitted work.

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Authors and Affiliations

Carlo P. Marinello[1] · Rudolf Brugger[2]

✉ Carlo P. Marinello
c.marinello@bluewin.ch

Rudolf Brugger
rudolf.brugger@zirkonzahn.com

[1] Voltastr. 33, Zurich 8044 CH, Switzerland

[2] An der Ahr 7, Gais 39030 BZ, Italy