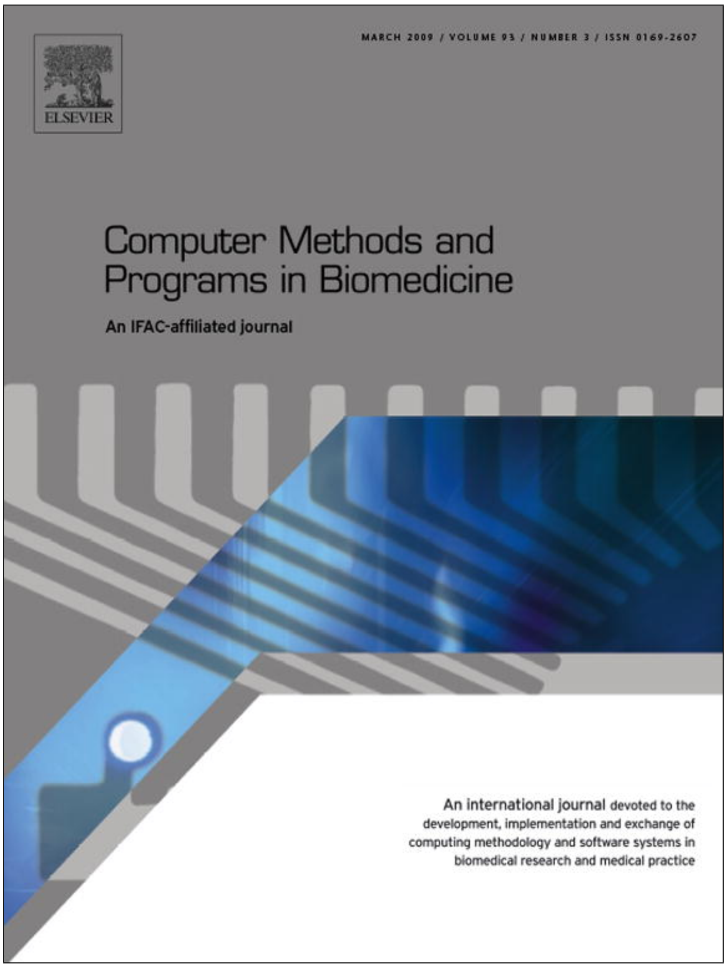
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Study on CAD&RP for removable complete denture

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ABSTRACT

This study explored a method for fabricating removable complete denture aided by CAD&RP technology. 3D crossing section scanner and laser scanner were respectively applied to obtain the surface data of artificial teeth, edentulous models and rims made in clinic. The vertical and horizontal relations of models were recorded before scanning with a special device. A 3D graphic database of artificial teeth, which can be aligned with parameters, was established. Special CAD software developed by ourselves was applied to the 3D integrated design process including automatic setting up artificial teeth, semiautomatic designing aesthetic and individualized artificial gingiva and base plate, automatic constructing individualized virtual flasks according to the finished CAD digital models of removable complete denture. At last, 3DP technology was used to make the individualized physical flasks. In this study, AMT and classic denture materials were effectually combined to achieve making removable complete denture aided by CAD/RP technology.

1. Introduction

To date, CAD&CAM (Computer Aided Design & Computer Aided Manufacturing) technology has made no noteworthy inroads into removable complete denture. We want to present a new area of application for this in our study. CAD&RP (Rapid Prototyping) technology was used to make individualized flasks for removable complete denture. For this target, a 3D graphic database of artificial teeth for parameterization positioning was established, the 3D scanning of the edentulous models and rims was carried out and special CAD software, which can realize automatic design functions, was developed.

2. Background

According to the Third National Epidemiological Survey on Oral Health [1] in 2005, 6.82% of elders aging from 65 to 74 were edentulous in China. Based on the Chinese Fifth Population Census in the same year, there were about 7.69% of total people aging from 65 to 74. Hence, there were about seven million edentulous patients in China in 2005. By now, removable complete denture has still been the main dental prosthetic restoration for them.

In the recent 20 years, dozens of dental CAD&CAM systems have been presented for inlay, crown, veneer and fixed partial denture. However, the development on

Abbreviations: CAD, Computer Aided Design; CAM, Computer Aided Manufacturing; RP, Rapid Prototyping; AMT, Advanced Manufacturing Technology; 3DP, Three Dimensional Printer.

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CAD&CAM for removable complete denture has been very slow.

From 1986 to 2004, Peijun Lü group [2–4] tried to produce teeth set-up curves with power function "$Y = A|X|^B$", created a positioning coordinate system for each tooth based on "surrounding box", developed software for setting up teeth and driving robot hand to position artificial teeth for removable complete denture. However, this technology route was not definite and practicable, and the base plate could not be fabricated. Maeda et al. [5] used 3D laser scanner to obtain the data of closed mouth impression of the edentulous jaws made in clinic, and get the data of artificial dentition and base plate made by dental technician. After the data registration in computer, the digital model of complete denture was created on screen. Meanwhile, Numerical Control Processing Equipment was used to fabricate plastic shells of dentition and base plate. Then, tooth-color and gum-color acrylic resin were respectively filled into the shells to make complete denture. However, we cannot find the application of CAD in the study and the craft used for fabricating removable complete denture was not practicable. Busch and Kordaß [6] scanned the edentulous models and explored software to analyze the reference structures that are anatomically important for the set-up of artificial teeth. With this software, occlusal plane could be defined, and the alveolar ridge centers of the maxilla and mandible were connected to form a surface which intersected the occlusal plane and marked the dental arch line. The artificial teeth were automatic selected and set up to position a special "posterior teeth set-up aid" device. The method for setting up the teeth database, positioning the teeth, designing the base plate and fabricating the complete denture was not involved in the article.

The literature review shows that within the latest 20 years, in the field of designing and fabricating removable complete denture aided by computer, no more than 10 publications can be found and no successful system has been introduced into the market. That is to say, AMT (Advanced Manufacturing Technology) has not been successfully applied in this field. Why? A first challenge exists in positioning the teeth with the computer and software. It requires sufficient mathematic descriptions for each tooth. The second challenge is found in the manufacture. Traditional CAM or RP technology (or the materials have been used in these technologies) cannot be directly applied to make removable complete denture.

Hence, in this study, we want to define sufficient and necessary mathematic descriptions with definite logic relations for each tooth, form a clear route for designing and fabricating removable complete denture aided by AMT, and develop special CAD software platform.

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3. Design considerations

The main software used in CAD step was Imageware 11 (EDS Company, USA). It could be applied to the design of many complicated 3D objects. It provides abundant tools for designing 3D points cloud, line/curve and surface. The designed data can be 3D displayed, moved and rotated along any coordinate axis. It also provides the interface for continuous development.

Firstly, a 3D graphic database of artificial teeth for parameterization positioning was established. In the next step, CAD route for removable complete denture was explored by the specialists both in removable complete denture and in computer graphics by means of interactive manipulation. After that, continued development with "Scoll" programming embedded in Imageware 11 was carried out by the specialist in computer programming to achieve highly automatic design function.

With the CAD software we developed, the reference structures that are anatomically important for setting up artificial teeth should be automatically detected or constructed on the 3D scanning data of the edentulous models, such as the alveolar ridge centerlines and the fullness sign surface on the upper rim. The occlusal plane should be semi automatically defined and the curves for setting up teeth should be created automatically. After these design features have been defined, artificial teeth should be selected from database and set up automatically. The dental technician can assess the aesthetics and functions of the suggested teeth set-up on the computer screen and can make slight corrections if necessary. After the base plate and "virtual flasks" have been designed, physical flasks should be fabricated aided by RP technology.

4. System description

4.1. *Established 3D graphic database of artificial teeth for parameterization positioning*

3D automatic crossing section scanner (SB-01, Accuracy: 0.04 mm, Beijing Shidai Tianshi Biological Technology Co. Ltd., Beijing, China) (Fig. 1a) was used to scan artificial teeth and STL format data was got (Fig. 1b).

4.1.1. *Created observation planes and observation major axis (Fig. 1c)*

In order to analyzing artificial tooth from the direction of morphology, firstly, the observation planes should be defined. On the software platform of Imageware 11, STL data of artificial teeth was imported one by one. According to the anatomically morphological characteristics, the middle sagittal observation plane and the coronal observation plane for each tooth were created, and the imaginary occlusal plane was created vertically to them. The crossing line of the middle sagittal and the coronal plane was extracted and regarded as the observation major axis.

4.1.2. *Created parameters for each tooth (Fig. 1d)*

Table 1.

4.1.2.1. *Positioning landmark points and positioning coordinate system.* For all the anterior teeth and the maxilla posterior teeth, the positioning landmark points and the positioning coordinate system binded to each tooth were used to control their space position and stance.

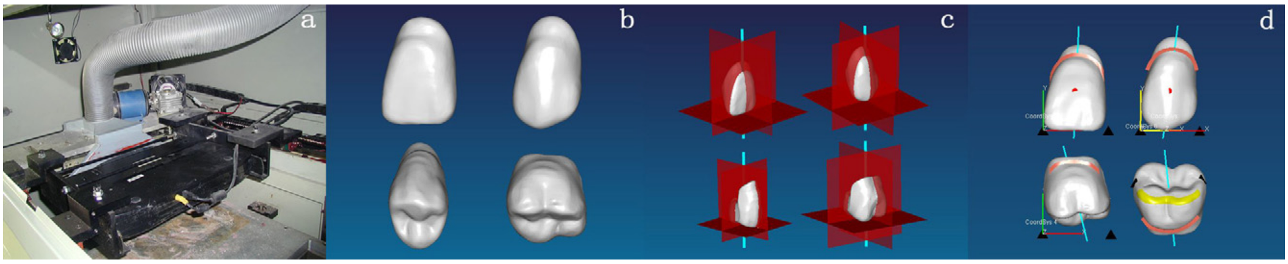

Fig. 1 – Set up 3D graphic database of artificial teeth (a) 3D automatic crossing section scanner. (b) 3D data of artificial teeth. (c) Observation planes including middle sagittal, coronal observation plane and imaginary occlusal plane. (d) Typical teeth in database, the coordinate systems are for anterior and maxilla posterior teeth positioning, blue lines is observation major axis of each tooth, pink surfaces are gingiva of each tooth, black filled triangular are landmark points for tooth positioning. Red points on maxilla anterior teeth are fullness sign points. Yellow area on mandible posterior tooth is the function cusps and their slopes.

At first, the height of contours of each tooth's mesial and distal surface were extracted along the direction of the observation major axis, then the "Project Cloud on Surface" function (Create cloud that are projections of the selected surface in the normal direction.) was used to create the projection points of all height of contours on the imaginary occlusal plane. Thus the mesial and distal positioning landmark points for each tooth were obtained. The above two points and the imaginary occlusal plane could be combined to create the positioning coordinate system.

For the mandible posterior teeth, the mesial and distal positioning landmark points were set on the crossing area of marginal ridge with the central fissure on the occlusal surface of each tooth.

4.1.2.2. Fullness sign point. To a removable complete denture, it is one of the most important rules that the maxilla anterior teeth should contribute to maintain the fullness (the position and form in labial/lingual direction) of the upper lip. A fullness sign point was extracted on the labial surface of each maxilla anterior tooth to be the reference when its labial/lingual stance was adjusted by software automatically.

4.1.2.3. Occlusion collision interference detection areas. In order to realize the centric balanced occlusion, the functional cusps and their slopes of each mandible posterior tooth were extracted to be the "Occlusion collision interference detection areas (final positioning evidence)" for adjusting their space stance.

4.1.3. *Set initial space stance for each tooth*

Considering the aesthetics and balanced occlusion, the space stance of all the anterior teeth and the maxilla posterior teeth were preset based on the statistical values of the dental crown's space stance of Chinese individual normal occlusion [7] and artificial teeth set-up rules [8]. The setting included the axis tilt angle and torque angle of the anterior teeth, and the space relation with the imaginary occlusal plane of all the anterior teeth and the maxilla posterior teeth.

4.1.4. *Created marginal gingiva at labial/buccal surface and gingiva margin at tongue/palate surface for each tooth*

"Flange Surface" function (Builds a surface that begins at the designated surface edge(s), curves on surface, trim curves, or 3D curves and extends away from that curve using the depth and angle you specify. A surface will be created whenever possible.) was applied to create the marginal gingiva with the width of 0.5 mm and at an angle of 135° to the labial/buccal surface of tooth. "B-Splines" function (Interactively creates a cubic B-spline interpolating curve from the specified points and with the designated constraint. Use this command to create curves from data to the requirements of your application.) was used to create the boundary curve of base plate at the tongue/palate surface of each tooth.

Table 1 – The parameters created for each tooth.

Tooth name	Parameters					
	Positioning landmark points	Positioning coordinate system	Fullness sign point	Occlusion collision interference detection areas	Initial space stance	Marginal gingiva/ gingiva margin
Maxilla anterior teeth	+	+	+	–	+	+
Mandible anterior teeth	+	+	–	–	+	+
Maxilla posterior teeth	+	+	–	–	+	+
Mandible posterior teeth	+	–	–	+	–	+

Note: "+" means "Yes", "–" means "No".

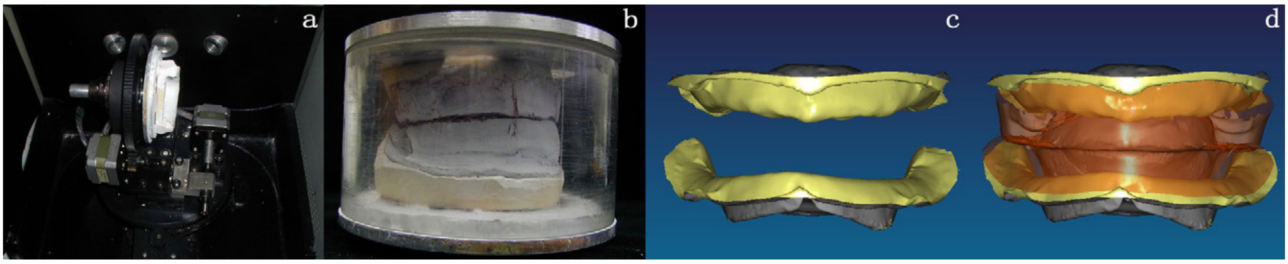

Fig. 2 – Scan models and rims. (a) 3D laser scanner. (b) Models relation locator. (c) 3D data of upper and lower edentulous models. (d) 3D data of the rims (orange parts).

4.2. *Got 3D data of edentulous models and rims in centric relation*

3D point laser scanner (Fig. 2a) [9] was used to scan the upper and lower edentulous models and rims in turn that had been obtained by dentist in clinic.

The edentulous models recorded the anatomic shape of the edentulous jaws and the post-dam zone that had been carved by dentist in advance. The rims recorded the individualized information such as the vertical and horizontal relation, the position of occlusal plane, the facial midline and the fullness requirements of the upper lip.

Before scanning, the "models relation locator" (Fig. 2b) [10] was used to record the vertical and horizontal relation. After scanning, the 3D STL data of edentulous models and rims in precise relation was got (Fig. 2c and d).

4.3. *Explored CAD route and develop software for removable complete denture*

4.3.1. *Created occlusal plane and world coordinate system (Fig. 3a)*

Occlusal plane was the prerequisite for teeth set-up. Based on the occlusal part of the upper rim that dentist had made in clinic, an accurate and individualized occlusal plane was got.

The crossing point of the incisal margin curve of upper rim and the facial midline was set as zero. Meanwhile, "Construct Uniform Surface from cloud" function (Creates 3D B-spline surface of a specified degree by approximating the selected point cloud.) was used to fit the occlusal part of upper rim as occlusal plane by passing through the point zero. The middle sagittal plane was vertical to occlusal plane and passed through facial midline.

The occlusal plane was set as XY plane, and the middle sagittal plane was set as YZ plane. The two planes were used to define a Cartesian world coordinate system together with the zero point.

4.3.2. *Created teeth set-up curves*

The teeth set-up curve of maxilla anterior teeth was created by projecting the incisal margin curve of upper rim to the occlusal plane (Fig. 3b).

The teeth set-up curve of mandible anterior teeth was got by offsetting the teeth set-up curve of upper anterior teeth to the lingual side on the occlusal plane (Fig. 3b).

The alveolar ridge center curves of the maxilla and mandible were connected to form a surface, which intersected the occlusal plane and the teeth set-up curve of maxilla posterior teeth was got (Fig. 3c).

The teeth set-up curve of mandible posterior teeth would be obtained after the maxilla posterior teeth had been set up.

4.3.3. *Set up the artificial teeth*

4.3.3.1. Set up the anterior teeth and maxilla posterior teeth. In the database, positioning coordinate system can express the requirements for space relation between each tooth and the occlusal plane. In order to set up these teeth, a paired coordinate system for each tooth on individualized occlusal plane would be created.

The mesial and distal positioning landmark points for each tooth were extracted from the teeth set-up curve. Except that the mesial landmark point of central incisor was the crossing point of teeth set-up curve and facial midline, the mesial landmark points of other teeth were the distal landmark points of their mesial adjacent teeth.

Based on the mesial and distal positioning landmark points and the occlusal plane, the positioning coordinate system for each tooth was established.

Each tooth was preliminarily positioned and probed for interference or excessive space towards its mesial tooth using the "Collision Detection" function (programmed by ourselves) based on the "Least-Square Method". If such an incidence occurred the tooth was moved along the teeth set-up curve until the data interference value was close to zero (Fig. 3d and e).

For maxilla anterior teeth, the linking line of the mesial and distal positioning landmark points was taken as rotation axis and each tooth was rotated toward the labial or lingual side to meet the labial part of the upper rim so as to satisfy the requirements of lip fullness (Fig. 3h).

4.3.3.2. Set up the mandible posterior teeth. "Project Curve to Surface" function (Projects a curve or a part of a curve onto a surface in the direction specified, within a specified tolerance) was called to project the teeth set-up curve of maxilla posterior teeth along the normal direction of plane to the occlusal parts of maxilla posterior teeth, then the teeth set-up curve of mandible posterior teeth was got (Fig. 3f).

The corresponding points of the mesial and distal positioning landmark points of mandible posterior teeth were extracted from the mandible posterior teeth set-up curve.

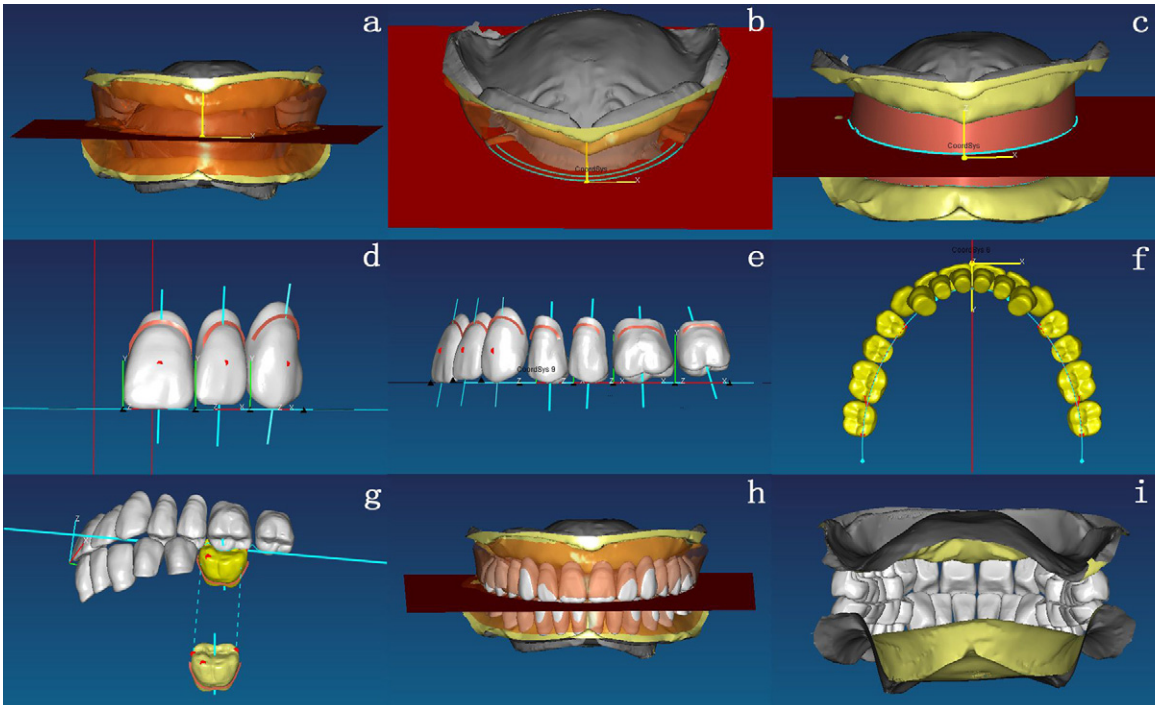

Fig. 3 – Set up artificial teeth. (a) Occlusal plane (red plane) and world coordinate system (yellow coordinate system). (b) Anterior tooth set-up curves. Labial blue curve is maxilla anterior tooth set-up curve, lingual blue curve is mandible anterior tooth set-up curve, and red plane is occlusal plane. (c) Maxilla posterior tooth set-up curve (blue curve). Pink surface is the surface between the alveolar ridge center curves of maxilla and mandible. (d) Set-up anterior teeth. (e) Set-up maxilla posterior teeth. (f) Create mandible posterior tooth set-up curve (red dash line). The blue curve is maxilla posterior tooth set-up curve. (g) Set-up mandible left first molar. The light yellow tooth is still not positioned, the deep yellow one is preliminarily positioned, blue dash lines show the corresponding relation between the landmark points and their paired ones, and horizontal blue long line is axis for tooth rotation. (h) Labial view of the teeth arch. (i) Lingual view of the teeth arch.

"Stepwise Alignment" function (Registers or aligns a group to a coordinate frame in an order dependent manner, based on matched pairs of corresponding geometric elements in the group and those in the coordinate frame) was called to preliminarily position mandible posterior teeth (Fig. 3g).

"Collision Detection" function based on "Least-Square Method" was called to calculate the interference value or distance value between each tooth's functional area and occlusal part of upper teeth arch. The linking line of mesial and distal positioning landmark points of each mandible posterior tooth was taken as the rotation axis to rotate each tooth toward buccal or lingual side until the interference value was close to zero.

The artificial teeth were set up (Fig. 3h and i), the dental technician can assess the aesthetics and functions of the suggested teeth set-up on the screen and make slight corrections if necessary.

4.3.4. *Design artificial gingiva and base plate*

Based on dental arch and the edentulous models, the gingiva and base plate were designed semiautomatically.

"B-spline" function was used to create the border curve of the base plate at the tissue side, and then the border curve at the polished side was constructed automatically. The boundary between the teeth and the base plate could be obtained through respectively matching each tooth's labial/buccal marginal gingiva and each tooth's lingual/palatal side gingival margin that had been created in database (Fig. 4a). The palatal reggae data on the maxilla edentulous model was extracted and thickened by 2 mm with "Points-cloud Offset" function (Creates new point clouds by offsetting selected point clouds based on a specified offset value.) (Fig. 4c). "Loft Surface" function (Creates a B-spline surface by lofting (n) independently selected 3D curves.) was called to finish constructing the polished surface of base plate. The surface of edentulous alveolar ridge within the border curves was extracted to be the tissue surface of the complete denture (Fig. 4b).

"Sweep Surface" function (A path curve is the path along which the generator curve will be swept. A generator curve is the profile that will be swept along the path curve to create the surface. By defining two path curves, the surface extends to the limit of both path curves.) was called to create hemispherical base-plate edge. The border curves at the tissue side and polished side were taken as the path curves, and the hemisphere was taken as the generator. The diameter of the hemisphere was 2 mm and can be set freely if necessary (Fig. 4d).

The base plate was finished (Fig. 4e).

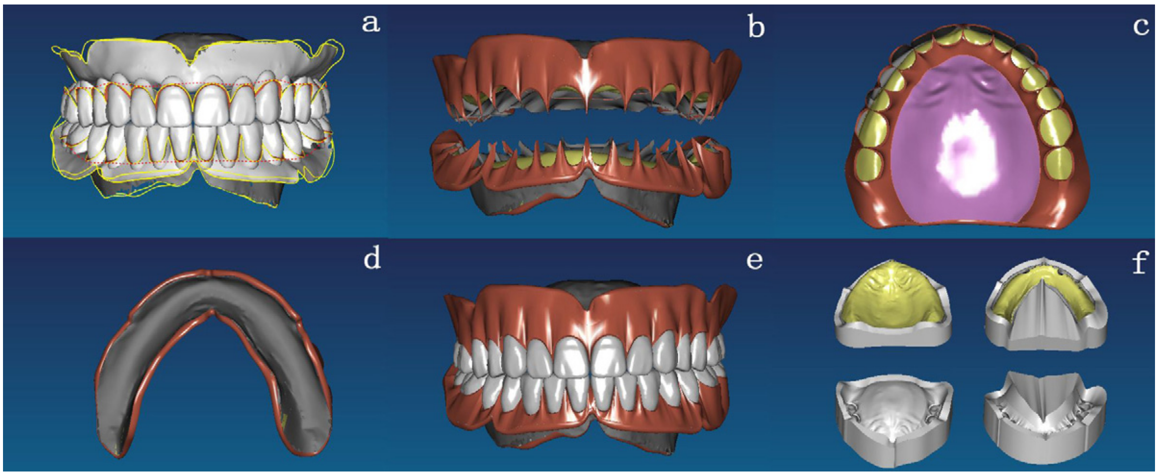

Fig. 4 – Design gingiva, base plate and virtual flasks (a) Border curves of base plate (yellow curves). (b) Polished surface of the base plate. (c) Palatal rugae part of upper base plate. (d) Hemispheroid edge of base plate. (e) Finished complete denture digital models. (f) Virtual flasks.

4.3.5. *Design individualized virtual flasks*

Based on the designed removable complete denture, the individualized virtual flasks were designed, and the internal shape of them was the same as the traditional physical flasks without wax base plate and artificial teeth (Fig. 4f).

4.4. *Fabricate physical flasks*

Z Printer 310 plus (resolution: 300 × 450 dpi, layer thickness: 0.089–0.203 mm, Z Corp, USA) is a kind of 3DP (Three Dimensional Printer) machine. It can create physical models from CAD data by using an inkjet print-head to deposit a liquid binder that solidifies layers of powder. The material we selected is a kind of high performance composite which is harmless to human.

The CAD data of the virtual flasks were printed to physical individualized flasks by the Z Printer 310 plus.

4.5. *Finished the removable complete denture*

The artificial teeth were inserted into the flasks one by one, and the traditional laboratory procedures including packing and polishing need to be used to finish the removable complete denture.

5. Status report

An initial setup for designing and fabricating removable complete denture aided by CAD&RP technology was successfully performed and the system's feasibility was established. Five removable complete dentures have been successfully designed and fabricated aided by this system. On the edentulous plaster models, the dentures were in good fitness and centric balanced occlusion.

However, the whole system is still in experimental set-up phase at present, and the evaluation of reliability and accuracy was preliminary and qualitative. In the next step, laboratory quantitative tests and clinic experiments will be carried out in order to improve and practice the system.

6. Lessons learned

6.1. *About teeth database and teeth selection*

The method for setting up 3D graphic database of artificial teeth is directly correlated to the CAD route design. However, we cannot find definite descriptions about it in the studies before [2–6]. In order to use classic teeth set-up theory based on morphology [8] when designing CAD software for removable complete denture, we defined three observation planes including middle sagittal plane, coronal plane and imaginary occlusal plane for each tooth according to the anatomical and morphological characteristics.

In this study, only one set of artificial teeth has been selected for designing. In the near future, we will expand the database and add automatic teeth selection function to the system.

6.2. *The contribution of rims*

Despite the possibility of defining the position of each maxilla artificial tooth only by analyzing the edentulous models [2–4,6], it is very difficult to satisfy the individualized requirements such as the fullness of the upper lip, the movement space of the oral soft tissue and some aesthetic rules of removable complete denture. The rims made in clinic can be taken as better reference to make a good decision on individualized and compatible maxilla anterior teeth positions of the removable complete denture. Based on incisor margin curve on the upper rim, the maxilla and mandible anterior teeth set-up curve can be created. The crossing point of the teeth set-up curve and the facial midline on the upper rim is the mesial landmark point of central incisor. Moreover, the labial part of upper rim expresses the fullness requirement of the lip and the maxilla anterior teeth. Therefore, in this study, the rims were 3D scanned and regarded as the original basis of CAD process.

6.3. *The realization of balanced occlusion*

Balanced occlusion is one of the most important factors for the functional stability of removable complete denture. It was not involved in studies before [2–7].

To anatomical artificial teeth, the space stance of each posterior tooth needs to be exactly set to fit the requirements of protrusive balanced occlusion and lateral balanced occlusion [8]. As well known, there are objective limitations in traditional setting up teeth operations. In virtual environment, the space position relationship among artificial teeth or between each artificial tooth and the occlusal plane can be accurately set by the software.

In the software, the positioning coordinate system of each tooth (exclude the mandible posterior teeth) in database can express the exact space relation between each tooth and the occlusal plane based on the requirements of balanced occlusion, and the teeth set-up curves are used to express the individualized requirements for the location and shape of the teeth arch. Hence, when each tooth is "carried" to its position on the curve by the positioning coordinate system, the "Mediolateral Curve" and "Spee's Curve" of the dental arch can be got.

The mandible posterior teeth set-up curve pass through the contacting zones within the occlusal parts of maxilla posterior teeth and can fully show the space stance of functional contact areas. After mandible posterior teeth have been preliminary located with the mesial and distal positioning landmark points on the lower posterior teeth set-up curve, their "functional fossas" contact upper "functional cusps". Through buccal/lingual rotation based on the collision interference detection, lower "functional cusps" contact upper "functional fossas". By now, the balanced occlusion can be realized in vitro.

6.4. *Combination of AMT and classic denture materials*

The base plate of complete denture and artificial teeth were composed of two kinds of materials with different colors and textures. The form of the integration part (i.e. the marginal gingiva) is very complicated. Therefore, both the existing CAD/CAM and RP technology cannot be directly used to make practicable removable complete denture. Meanwhile, the classic materials used for removable complete denture are verified to be competent. Based on the above considerations, we carried out the "Two-Step" method to make complete denture aided by CAD/RP technology.

Step one, we utilized 3D laser scanner to get data, CAD technology to achieve integrated design of removable complete denture including teeth set-up, gingiva and base plate design. Using CAD&RP technology to design and fabricate individualized physical flasks. Step two, the conventional laboratory procedures and classic denture materials were used to finish the dentures.

The above method combined AMT and the classic denture material. It greatly simplified the complicated procedures of traditional handicraft, relieved workload and improved the accuracy of restorations.

7. Future plans

In the near future, we will carry out a strict clinic experiment to analyze the accuracy and the stability of the system. Meanwhile, we plan to explore a program module of virtual articulator for CAD software.

Conflicts of interest

None declared.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cmpb.2008.10.003.

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