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Laser Medical Image Reconstruction and Computer Aided Design of Polymethyl Methacrylate for Pediatric Removable Space Maintainer Applications

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Background: Premature loss of primary teeth is a common problem in pediatric dentistry, resulting in disruption of arch integrity. Hence, space maintainers (SM) used for maintaining space are necessary. However, current methods of making removable space maintainers (RSM) have some limitations. *Methods*: Digital model of dentition defects were obtained using scanning technique coupled with laser medical image reconstruction. The digital RSM were designed using 3 shape software. They were manufactured using two methods: Polymethyl methacrylate (PMMA), and conventional methods. The spaces between the tissue surfaces of the RSM and the models were replaced using silicone, the maximum, mean distances and standard deviation were measured. A three-dimensional variation analysis was used to measure these spaces. The variance test compares the difference in distances among various materials. *Results*: The PMMA RSMs fit the models well. The maximum and mean distances of the PMMA groups were significantly smaller than those of conventional group ($p < 0.01$). Furthermore, there were no significant different for the standard deviations among PMMA group and the conventional group. *Conclusion*: Digitally designed and integrated RSMs have good suitability and were better than that of conventional method. PMMA manufactured RSM using CAD/CAM technique may be applied to clinical.

Keywords: Laser Medical Image Reconstruction, CAD/CAM, Removable Space Maintainer, Pediatric Dentistry, Polymethyl Methacrylate.

1. INTRODUCTION

Premature loss of primary teeth is often seen in pediatric dentistry, causing the disruption of arch integrity and adversely affecting the proper alignment of permanent successors [1]. Keeping a tooth in its proper position in the arch is the result of an interaction of forces, once out of balance, a change in the position of the tooth will happen. After the deciduous teeth were lost early, the adjacent and paired teeth shifted to the lacunar position, making the proximal and distal middle diameter and vertical diameter of the gap smaller. In related studies of Srivastava et al., nearly 50% of the first molar premature loss and 70% of the second molar premature loss were observed to be followed by some degree of reduction or closure of the missing tooth space. Hence, space maintainers (SM) frameworks [2] are used to maintain the space [3]. Removable space maintainer (RSM) is a kind of SMs, when contiguous primary molar teeth loss, removable space maintainer is well recommended [4]. There are several advantages to use RSM [5], such as maintaining the proximal, distal, and middle lengths of the space, maintaining vertical height, playing a role in restoring aesthetics [6], preventing speech disorders [7], and eliminating "bad habits" such as unilateral chewing. However, conventional RSMs have a few drawbacks, particularly in terms of their design and manufacturing. For example, the manufacture of RSMs is complicated, because it is highly technically sensitive, requires experienced technicians, and exhibits large individual variation. In addition, as the manufacture of RSMs are made of curved snap rings and self-curing resin, it is difficult to ensure the precision of snap rings in space maintainers. At present, PMMA commonly used in clinical is mostly generated by methyl methacrylate powder and liquid (monomer) through chemical curing or thermal curing reaction. In the polymerization reaction, it is hot and easy to form bubbles. Traditional denture base materials all have volume shrinkage in the process of molding and curing. Taking self-curing base resin as an example, the volume shrinkage in MMA

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monomer polymerization process is about 21%. And PMMA disk is different from the traditional PMMA material, CAD/CAM technology using PMMA material has carried on the improvement on the process, which is an industrial material made into the disk, in the process of preparation process has completed the polymerization shrinkage, therefore in the process of CAM cutting will no longer occur deformation, which will be better than the traditional craft production restoration form stability, its precision is more accurate. During the polyreaction of self-curing resin, the shrink occurs [8] and then the fitness between the tissue surface of the retainer and the mucosa between the snap ring and the abutment is inaccurate. As a result, pediatric patients adapt poorly to space maintainers. Furthermore, owing to the scarcity of artificial deciduous teeth products on the market, artificial permanent teeth products are usually modified to emulate the functionality of deciduous teeth; however, they do not accurately simulate their morphology. Hence, a precise, convenient and rapid design and manufacture method is needed to address these problems.

As we all know, computer-aided design and manufacturing (CAD/CAM) has been used since the 1980s [9, 10]. CAD/CAM technology has gradually developed into an alternative to traditional prosthodontics, which has the advantages of making prosthodontics more standardized, more repeatable and more efficient, and is conducive to promoting the popularization and application of new dental materials. CAD-CAM technology has many advantages such as standardized production, high efficiency and good repeatability. It is now widely used in dentistry, for oral medicine, particularly especially in prosthodontic [11, 12, 13]. CAD/CAM restoration is more stable and durable than traditional restoration when using the same material [14]. Currently, digital design techniques and rapid molding are mostly used to design removable partial denture (RPD) metal scaffolds [15] and manufacture their resin models [16] or directly manufacture the RPD metal scaffold [17–22], respectively. And it was used in Orthodontic dentistry, such as orthodontic space maintainers [23]. Kaihara et al. [24] compared the accuracy of measurements of digital models obtained using a noncontact 3D measuring system, pertaining to direct measurements made on plaster models from children, suggested that primary dentition analysis of digital models has a high accuracy level, comparable to that of direct measurement of plaster models by digital calipers. And however, to our knowledge, few research reported the use of CAD/CAM to design and manufacture RSMs in pediatric dentistry. And this method might address the problems of traditional method to make RSMs.

CAD/CAM PMMA-based polymer is a special plastic with good surface properties [25, 26], high mechanical performance [27, 28], as well as good marginal adaptation [29], and good biocompatibility [30, 31]. It is used in fixed prosthodontics, such as crown bridge repair and healing abutments, and to fabricate the scaffold and snap rings of an RPD. It is widely used in the fabrication of clinical denture bases due to its good physiochemical, mechanical, and biological performances. PMMA can be easily cut and molded through CAD/CAM technology. CAD/CAM technology can cut the precise restoration edge of PMMA, which will not form suspension and excessive extension after bonding, and can be highly polished. The restoration body can be closely attached to the neck edge and smooth surface, which is conducive to the healthy recovery of gingival tissue to normal shape, and effectively prevents the accumulation of plaque, gingival inflammation and gingival recession. The hypothesis of our study is that the RSMs manufactured by PMMA using CAD/CAM design may better than conventional methods which made of artificial teeth and self-curing resin. Therefore, our aim is to analyse the application of CAD/CAM design for RSMs in pediatric dentistry and evaluate the fitness.

2. METHODOLOGY

2.1. Construction of a Digital Model for Dentition Defects

We used a standard negative model (NissinTM, China) to made superhard mixed dentition plaster (Type I dental plaster, PegasusTM, China) and scanned it in a three-dimensional (3D) model scanner (D800, 3Shape A/S, Denmark) to obtain digital models (Fig. 1(A)). A partial defect dentition model was constructed by removing the first and second deciduous molars on both sides of the standard model's mandible. Then, a clear digital edentulism model was obtained by scanning the partial model (Fig. 1(B)). To ensure that the digital arrangement requirements for artificial teeth were met by this model, the upper jaw model was also scanned and its occlusal relationship with the mandible model was studied.

2.2. Digital Design of Removable Space Maintainers

Dental software for CAD (Dental System 2018, 3Shape A/S, produced in Denmark) and reverse engineering software (Geomagic Studio 2014, Geomagic Inc., USA) were jointly used to design all components for the removable space maintainer.

Since the database in the 3-shape software does not include deciduous teeth and the anatomical differences between deciduous and permanent molars are vast, we had to construct an artificial digitized models of standard teeth crowns for this experiment. The complete standard digital jaw model data were then imported into Geomagic Studio 2014 software and the "constructing sample boundary" function was used to define the boundary of each tooth. The processed information is then exported in stereolithography (STL) format. Note that anatomical and implant database in the anatomy element was selected from the control panel of the 3-shape software. The new database was created by clicking "Add" under the Database menu and called the "deciduous teeth database." The model in the scan database was clicked and the constructed teeth data were imported into the database. Then we used "Scan It Library" for tooth editing. (Fig. 2(A)) Bottom cutting, dental crown changing, dental crown shrinking, debris removal, and boundary and deformation point addition were performed. Then, the models in the teeth database were edited. The teeth sequence and positions were arranged according to professional requirements and "smile editing" was performed. Hence, the construction of the DIY s was completed.

The RPD + temporary tooth design module in 3-shape Dental System 2018 was selected. The RPD module is used to design the denture base and the temporary tooth module is used to design the artificial teeth. As space maintainers are transitional fixed prosthodontics, the selection of materials for space maintainers is different from that for RPD in adults. During the growth and development phase, snap rings at the buccal side of the teeth are used minimally to avoid limiting the growth of the width of the dental arch. Note that effects of maintainer base on the jaw and

Fig. 1. (A) Standard digital dental model. (B) Standard digital defect dentition model for mandibular dentition.

dental arch are considered in the design. Therefore, the design for the base should be short or have no vestibular base but a long lingual base. Under conditions in which the mandible is fastened, snap rings are not necessary and fixation is solely dependent on the lingual base.

The sites of missing teeth were labelled on the mandibular edentulism digital model, following which the digitized models of standard teeth crown were imported into the software. Virtual articulator function was used to adjust the anatomical module of the artificial teeth to ensure the functionality of occlusion. The "major connector" design was chosen for the maintainer base and its thickness was set to the conventional size of 1.5 mm. Since the connector to the partial denture is relatively thin and is where the stress is concentrated, its thickness was increased to 2.5 mm. The lingual side of the base was extended to the distal and middle parts of the first molar to form a base for the removable space maintainer. The final set of removable space maintainer data were exported in STL format (Figs. 2(B∼I)).

A 5-axis numerical control milling machine (Organical Multi, R + K GmBH, Germany) was used to cut 20 PMMA material samples (Fig. 3(A)) into removable space maintainers. After removing the support structure, the maintainer was polished and fit on the superhard plaster model.

The mandibular edentulism model described in Section 1.1 was used to fabricate the conventional removable space maintainer. The base was fabricated by a Type 2 Class I denture base polymer powder (self-curing denture powder, 1R, biomimetic color, NISSIN, Japan) and Heraeus three-layer synthetic resin teeth (Heraeus GmBH, Germany). After the maintainer was fabricated, it was fit onto the superhard plaster model (Fig. 3(B)).

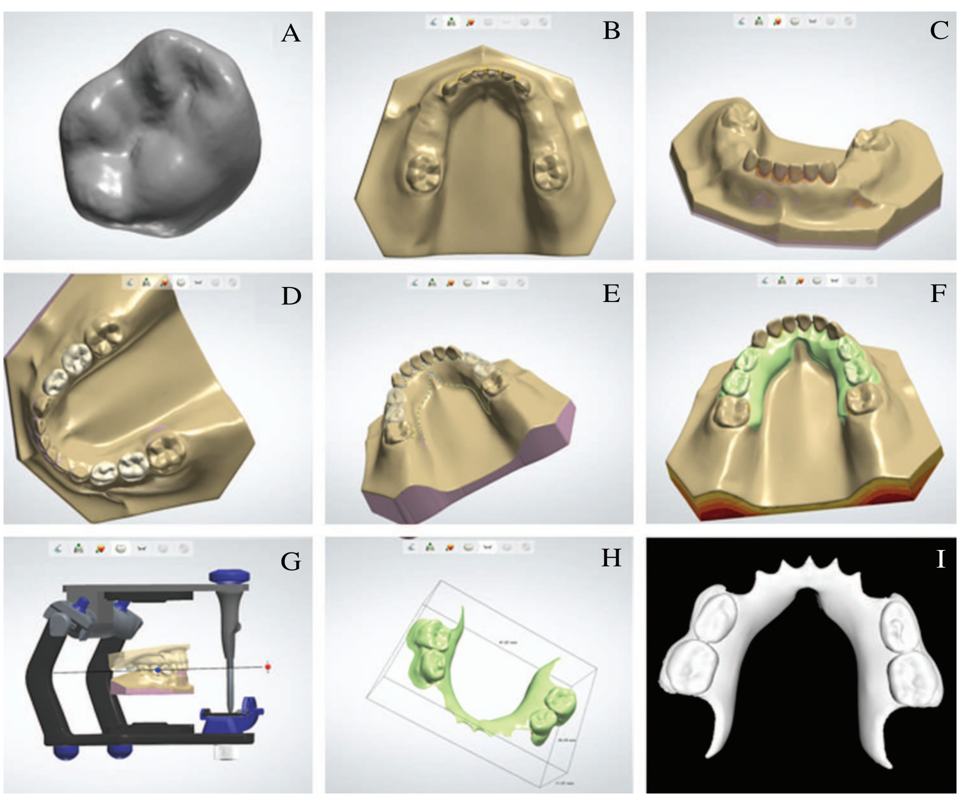

Fig. 2. Digital design process for removable space maintainers. (A) Artificial digitized models of standard teeth crown of mandibular right second molar tooth (B) Importing the model data (C) Observing the model and filling in the voids [21] (D) Importing the artificial teeth model from the DIY deciduous teeth database into the software (E) Constructing the profile of the major connector (F) Composing the integrated removable space maintainer (G) Using the fictitious articulator to perform occlusal adjustment (H) The final removable space maintainer (I) The final removable space maintainer data exported in STL format.

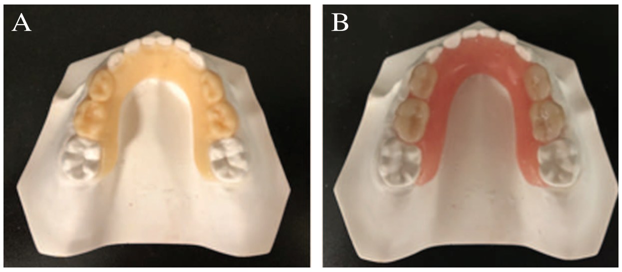

Fig. 3. (A) PMMA removable space maintainer. (B) Laboratory fabrication of removable space maintainers.

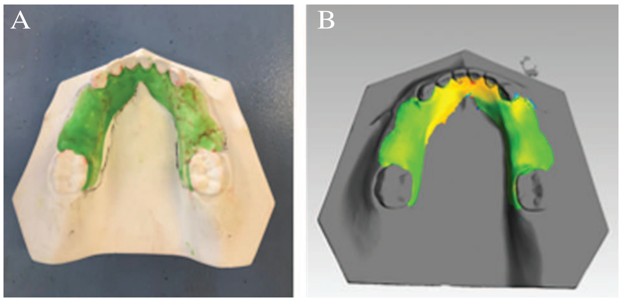

Fig. 4. Quantitative assessment of removable space maintainers. (A) Silicone film model data. (B) Digital silicone film model data.

2.3. Suitability of Different Morphological Components of Removable Space Maintainers

After the removable space maintainer was fit to the mandibular plaster model, a preliminary evaluation of the model's feasibility was performed through observations and a compression method. The assessment criteria for RPDs were used as a reference for the observations and are based on the principles proposed by Frank et al.: (1) whether all occlusal supports are completely in place; (2) whether the rigid components of the denture contact the corresponding abutment; and (3) no visible space greater than 1 mm exists between the main connector and the model. In this experiment, since no occlusal supports were involved, we only used the 2nd and 3rd of Frank's criteria for the assessment. In the compression method, a cement filler was used to compress the occlusal support vertically; suitability was considered good if the denture did not significantly warp.

For the quantitative assessment of removable space maintainers, a silicone impression material (Variotime Light Flow, Heraeus GmbH, Germany) was injected onto the tissue surface of the removable space maintainer [31]. The removable space maintainer was placed on the superhard plaster model. A vertical force of 20 N was applied for 10 min until the silicone had completely solidified. Excess silicone was removed to prevent the removal of the removable space maintainer, thereby affecting the analysis results. The space maintainer was removed and the silicone gel remained on the superhard plaster model.

A digital analysis method was then used to measure the space between the denture and the model [32]. A Smart Optics 880 Dental Scanner (Smart Optics GmbH, Germany) was used to obtain the corresponding digital silicone film model data. Sets of film model and raw digital model data were imported to Geomagic Studio 2014 software (Geomagic Inc., USA). Digital model data were fixed and set as the reference. The digital silicone film model underwent N-point registration and was set as the measurement subject. Three identical position points in the two models were selected for registration. The silicone film region in the digital silicone film model was selected as the measurement area and the 3D variation analysis function was used to calculate the mean differences in the selected area (i.e., the differences in the mean thickness of the silicone film) between the two models. At the same time, a variation chromatogram was generated to display the thickness of the silicone film in various regions (Figs. 4(A∼B)). The 3D variation analysis function can simultaneously calculate the maximum distance (positive) (i.e., the maximum thickness of the silicone film) for the two digital models; these data were recorded as the "maximum space," which was used to express the maximum space between the denture tissue surface and the model. This method was repeated for 20 model samples.

2.4. Statistics

SPSS 19.0 (IBM Inc., USA) was used for statistical examination of the data. Quantitative data were expressed as the mean ± standard deviation ($\bar{x} \pm s$). One-way ANOVA was implemented for the statistical analyses of the mean space, the maximum space, and their standard deviations in the conventionally fabricated and PMMA-integrated removable space maintainers. Note that of $p < 0.05$ was considered statistically significant.

3. EXPERIMENTAL RESULTS

3.1. Qualitative Assessment Results

Here, two types of removable space maintainers exhibited a good fit onto the superhard plaster standard model—there was tight contact between the denture base and the model and between the major connector and its lower plaster model; no 1 mm space was observed and no significant warping was present. The compression of the space maintainer components using the cement filler produced no significant warping, which conforms to clinical requirements.

3.2. Quantitative Assessment Results

The 3D variation analysis results showed that the mean spaces for the conventional space maintainer and the PMMA digital space maintainers were 41.44 ± 1.16 μm, and 41.90 ± 1.58 μm, respectively. The differences between the conventional and the PMMA digital space maintainers were statistically significant ($p < 0.001$). The maximum space values for the conventional and the PMMA digital space maintainers were 4.31 ± 0.13 mm and 4.16 ± 0.10 mm, respectively. The differences between the conventional space maintainers and the PMMA digital space maintainers were statistically significant ($p < 0.001$).

Table I. Comparison of markers between the two processing methods.

	Processing method			
Marker (mm)	Conventional group ($n = 20$)	PMMA group ($n = 20$)	F	P
Maximum distance	4.3066 ± 0.1265	4.1576 ± 0.1048	4.058	<0.001
Mean distance	0.0436 ± 0.0007	0.0414 ± 0.0012	6.792	<0.001
Standard deviation	0.3612 ± 0.0510	0.3378 ± 0.0392	1.393	0.172

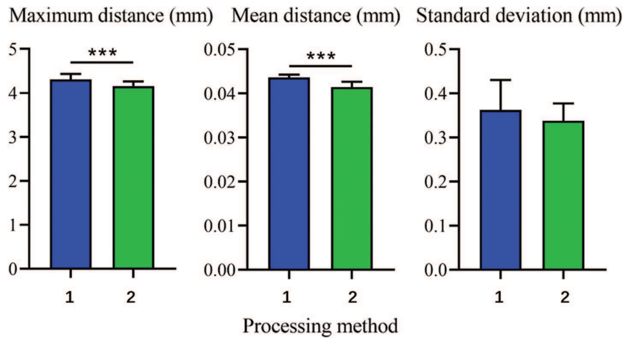

Fig. 5. (1) Maximum distance: There were significant differences in the maximum distance values for processing methods 1 (laboratory group) and processing methods 2 (PMMA group). (2) Mean distance: There were significant differences in the mean distances for processing methods 1 and 2; (3) Standard deviation: There were no significant differences in the standard deviations for processing methods 1 and 2.

In Table I, the maximum (positive) and mean distances of the PMMA group were significantly smaller than those of the conventional group, and difference were significant ($p < 0.05$). The differences in standard deviations for the conventional and PMMA groups were not significant ($p > 0.05$).

Maximum distance, mean distance, and standard deviations are shown in Figure 5. (1) Maximum distance: There were differences in maximum distances for processing methods 2 (PMMA group), and 1 (conventional group), which were all significantly different from the mean values in processing method 1. (2) Mean distance: There were significant differences in the mean distances for processing methods 1 and 2. (3) Standard deviation: There were no significant differences in the standard deviations for processing methods 1 and 2.

As shown in Figure 6, the top and bottom of the irregular bottle chart are the upper and lower limits of the maximum distance, mean distance, and standard deviation of the 20 samples (i.e., the data distribution range) studied for each processing method group. The wide region in the bottle chart represents the highest number of samples among the 20 samples in that processing method group. Conversely, the narrow region in the bottle chart represents the lowest number of samples among the 20 samples in that processing method group. The horizontal line in the graph represents the mean of 20 samples in that group, and the two dotted lines represent the distribution range for 95% of the 20 samples in that group. The symbols for significant differences are the same as in the previous figure.

As shown in Figure 7, when the maximum distance, mean distance, and standard deviations for 20 samples in the three processing method groups were arranged in ascending order, irregular curves represented by three different colors were plotted. Each point on the curve represents a sample value for that treatment group. The x-axis represents the sample numbers from 1 to 20.

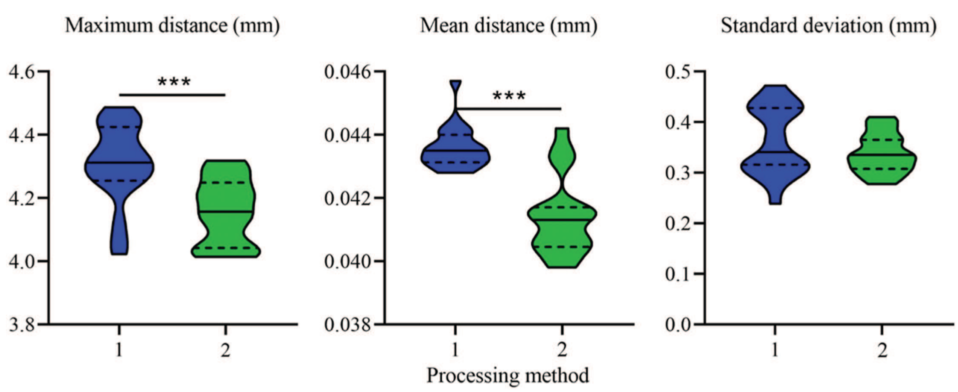

Fig. 6. The wide region in the bottle chart represents the highest number of samples among the 20 samples in that processing method group. Conversely, the narrow region in the bottle chart represents the lowest number of samples among the 20 samples in that processing method group. The horizontal line in the graph represents the mean of 20 samples in that group, while the two dotted lines represent the distribution range for 95% of the 20 samples in that group. The symbols for significant differences are the same as in the previous figure.

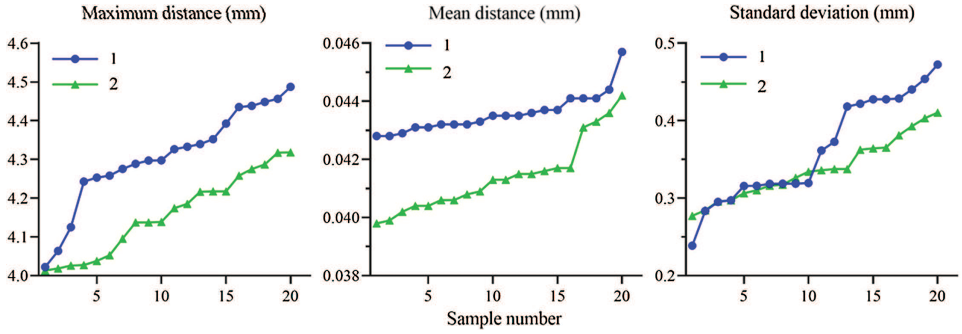

Fig. 7. Each point on the curve represents a sample value for that treatment group. The x-axis represents the sample number from 1 to 20.

4. DISCUSSION

Currently, digital design techniques and rapid molding are mostly used to design removable partial denture (RPD) metal scaffolds [15] and manufacture their resin models [16] or directly manufacture the RPD metal scaffold [17–22], respectively. Other denture components are still manufactured using conventional processes. Related research are not much, Soltanzadeh et al. [34] evaluated pertaining to overall accuracy and fit of conventional versus CAD/CAM RPD frameworks based on standard tessellation language (STL), and evaluated accuracy and fit of each component of the RPD framework. Virard et al. [35] proposed an innovative procedure for removable denture, based on use of an intraoral scanner, CAD with different software used sequentially, and CAM with a 5-axis machine in a case report. The prosthodontics department at the Peking University Hospital of Stomatology [36] has reported a case of a RPD completely manufactured using CAD/CAM. However, there were no reports detailing the use of CAD/CAM to design removable space maintainers. Studies on the area of digital technology using in other space maintainer are also rarely reported. To the best of the authors' knowledge, Kun et al. [37] designed space maintainer (band with loop) devices by CAD software, and manufactured by milling of the PEKK blocks. Ierardo et al. [38] made the orthodontic space maintainers in PEEK polymer through a digital workflow, however, they didn't design and use of artificial teeth. Soni [23] made a BruxZir zirconia space maintainer by digital methods for a female patient with chronic intra-radicular abscess in upper right first primary molar which was treated with extraction.

Our present study found that, based on the CAD/CAM system, maximum and mean distances for PMMA group were significantly smaller than those for conventional group, which indicates that materials of PMMA are promising for clinical applications. In this study, to qualitatively assess the compatibility of digitally designed removable space maintainers, visual observation and a compression technique commonly used in clinical treatment and research were employed. For quantitative assessment, we referred to reports by Stern et al. [32] and Dunham et al. [39], who measured the space between the denture and the model to assess the former's compatibility. However, we employed a 3D variation analysis commonly used in suitability assessment for fixed prosthesis to measure the space between the denture and the model [34]. Our results showed that the maximum and mean distances for the PMMA group were smaller than those for laboratory group, and these differences were significant ($p < 0.05$). The differences in the standard deviations for the laboratory and PMMA groups were not statistically significant ($p > 0.05$). The reason may be that the digital method makes the design precision and machining precision higher, and there is no polymerization shrinkage problem. Therefore, the compatibility of the digital removable space maintainers fabricated in this study is better than that of traditional ones, largely because the conventional fabrication of removable space maintainers is complex: model construction; polymerization shrinkage of the self-curing resin, grinding and polishing of the RSM are all prone to errors.

Digital technique has many advantages, in this study, digital design and fabrication simplified the manufacturing process, reduced deformation and errors, and improved the suitability of removable space maintainers. Apart from three case reports, there are few studies are on about using of PMMA polymer in pediatric dentistry. PMMA is used in the fabrication of clinical due to its good physiochemical, mechanical, and biological performances. However, currently, the intensity and color for PMMA are limited. When used in the frontal teeth region, the color of the base and the artificial teeth may affect the aesthetics. In addition, the color of PMMA maintainers can be improved by changing the performance of the material or by dyeing it. In future studies, we shall improve the intensity and color of the PMMA maintainers and the mechanical performance of various other removable space maintainers. Moreover, research on the wear resistance of PMMA artificial teeth is also underway.

In conclusion, we examined the feasibility of CAD/CAM to develop new PMMA-integrated removable space maintainers and validated CAD/CAM, which provides a foundation for future clinical applications. We have developed an original and creative method for combining digitalization technology and the clinical requirements of pediatric dentistry, exploring new possibilities. Design improvements and the search for new manufacturing materials require further research.

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