A preliminary study on a tooth preparation robot

Fusong Yuan & Peijun Lyu

ADVANCES IN APPLIED CERAMICS
2020, VOL. 119, NOS. 5–6, 332–337
https://doi.org/10.1080/17436753.2019.1666555

A preliminary study on a tooth preparation robot

Fusong Yuan[a,b,c,d,e,f] and Peijun Lyu[a,b,c,d,e,f]

[a]Centre of Digital Dentistry, Peking University School and Hospital of Stomatology, Beijing, People's Republic of China; [b]Department of Prosthodontics, Peking University School and Hospital of Stomatology; [c]National Engineering Laboratory for Digital and Material Technology of Stomatology, Beijing, People's Republic of China; [d]Research Centre of Engineering and Technology for Digital Dentistry of Ministry of Health, Beijing, People's Republic of China; [e]Beijing Key Laboratory of Digital Stomatology, Beijing, People's Republic of China; [f]National Clinical Research Center for Oral Diseases, Beijing, People's Republic of China

ABSTRACT
This is a study of a robot-controlled ultrashort pulse laser system used for tooth preparation to overcome drawbacks of traditional manual methods, thus improving its quality, precision, and clinical efficacy. Based on the international advanced digital technologies, automation technologies, and medical laser technologies, the entire tooth preparation process was completed autonomously using the robot-controlled ultrashort pulse laser. In the study, 15 extracted human first molars were prepared automatically by the robot system. And the result accuracy was evaluated using software. Compared with the CAD data of standard tooth preparation, the overall average error, preparation depth of the natural tooth preparation, and convergence angle were 0.05–0.17 mm, 2.097 ± 0.022 mm with an error of 0.097 ± 0.022 mm, and 6.98 ± 0.35° with an error of 0.98 ± 0.35°, respectively. The feasibility and accuracy of the robot-controlled femtosecond laser technique for tooth preparation were confirmed.

ARTICLE HISTORY
Received 14 May 2019
Revised 14 August 2019
Accepted 7 September 2019

KEYWORDS
Tooth preparation; robot; ultrashort pulse laser

Introduction

Tooth preparation is a procedure in which a clinician uses a high-speed turbine that drives various emery or tungsten-steel burs in the patient's mouth to grind the hard tissues of a tooth in order to prepare it as per a specific morphology [1]. It is the basic operation for the treatment of diseases affecting the dental hard tissues.

Currently, tooth preparation is performed in the clinic using hand held high-speed turbines or commercial dental lasers. Both these methods have obvious shortcomings and insufficiencies. First, the oral cavity is small, thus operation depends on the vision and hand positioning control of the operator, which often results in excessive or insufficient tooth preparation or iatrogenic damage to the gingival, labial, buccal, and lingual mucosae. Second, high-speed turbines generate high-pitched noises, which make both patients and physicians uncomfortable [2–5]. Third, current commercial dental lasers may stimulate the pulp, causing different degrees of pain in patients [6–8]. However, continuing the use of traditional manual operation in tooth preparation, but replacing mechanical power with laser power, cannot eliminate the limitations of manual operation.

Precision medicine is a consensus and direction of the international medical community. Therefore, the advantages of high precision, dexterity, and speed of robots can finally overcome the limitations of manual operation, and improve the accuracy and efficiency of clinical operation. Currently, robotic technology has been widely used in several fields of stomatology, and promoted its rapid development. In order to overcome the shortcomings of current manual tooth preparation techniques, we developed a robotic oral tooth preparation system and completed its preliminary validation in a clinical laboratory, thereby laying a foundation for its clinical application.

Materials and methods

1. Experimental equipment, software, and materials
   1.1. Independently-developed 'tooth preparation robot' mainly included the following six parts [1] (Figure 1):
      (1) Intraoral working end of the tooth preparation robot: lens focal length, 175 mm; two-dimensional scanning galvanometer spot scanning speed, 1900 mm s^{-1}; and Z-axis minimum step 0.1 μm and maximum step 10 mm;
      (2) Tooth preparation computer-aided design/computer-aided manufacturing (CAD/CAM) software;
      (3) Laser system: ultrashort pulse laser (wavelength, 1064 nm; pulse width, 15 picosecond; pulse repetition frequency, 100 kHz; power, 30 W; laser focus spot size, 38 μm);

CONTACT Peijun Lyu kqlpj@bjmu.edu.cn

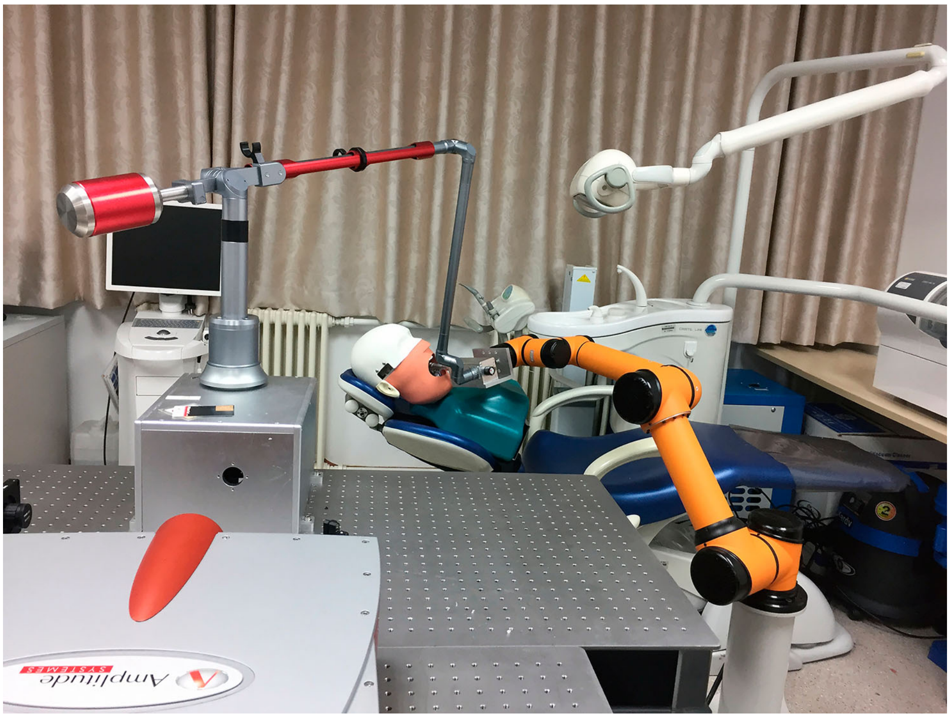

Figure 1. The tooth preparation robot.

the laser was focused using the 175 mm lens to ablation the tooth surface, and a charge-coupled device (CCD) took measurements of the focus area;
(4) 6-degree-of-freedom laser beam arm;
(5) Tooth positioner;
(6) Intraoral three-dimensional scanner (TRIOS, 3Shape, Denmark)

1.2. Sample stage position control device: micrometer (accuracy, 0.01 mm; Mitutoyo, Japan)
1.3. Three-dimensional measurement device: laser three-dimensional confocal microscope (VK-X200, Keyence, Japan) and three-dimensional measurement software (Geomagic qualify 2012, 3M, U.S.A.)
1.4. This study included 20 isolated natural teeth samples (maxillary and mandibular first molars) extracted due to periodontal disease in the Department of Oral and Maxillofacial Surgery, Peking University Hospital of Stomatology. Informed consent was obtained for the procedures.

Methods

Preparation of experimental samples

Twenty morphologically intact maxillary and mandibular first molars, freshly extracted due to periodontal disease, were collected from the Department of Oral and Maxillofacial Surgery of the Peking University Hospital of Stomatology. Informed consent was obtained from all patients before commencing the study. An ultrasonic scaler was used to remove calculus and soft tissue from the surface of the isolated natural teeth, and they were rinsed with normal saline. For five of the teeth, an emery ablationter (Shenyang Kejing, STX-202) was used to ablation the crown and root along the transverse outline of the enamel-bone boundary (cementoenamel junction). The emery wire was moved parallel to the cross-sectional surface towards the crown, and 5-mm thick samples were ablation. The two cross-sectional surfaces were manually polished and smoothened with 800- and 1000-mesh sandpaper and used for single-depth laser ablating measurement experiments of the isolated natural teeth (i.e. the depth of the ablation of the 5-layer laser pulse). The remaining 15 intact teeth were immersed in formalin solution until the automated tooth preparation process (Figure 2).

Determination of single depth of ablation

A picosecond laser research test platform was built *in vitro*, and the isolated natural tooth samples were fixed on the stage. A micrometer was used to adjust the position of the incident laser direction, so that the sample was ablation perpendicular to the beam axis and coincided with the focal plane of the laser. The laser parameters was set with the pulse energy of 300 μJ, a spot diameter of 38μm, and the scanning velocity 1900 mm s^{-1}. Two-dimensional scanning path of focal plane scanned five concentric circles of different diameters from small to large, and a concentric circle was scanned with five layers of pulses. The convex lens remained stationary during the entire scanning

Figure 2. Isolated natural tooth sample for single depth of ablation measurement.

process. The five isolated natural teeth samples were scanned with the laser according to this path, and the 50× lens of a laser three-dimensional topography measuring microscope was used to scan and measure the vertical height of the two adjacent concentric circles. Finally, a single depth of ablation (*the ablation depth with five layers of laser pulses*) of the isolated natural tooth was averaged and calculated (Figure 3).

CAD and layer-ablation automated tooth preparation for full-crown preparation

The 15 intact, isolated, natural teeth were fixed in the jaw model of the phantom head simulator. The three-dimensional data of the isolated natural teeth were acquired using an intraoral scanner. The tooth positioner was installed, and the three-dimensional data of the isolated natural teeth were acquired again. The two data sets were registered, and the individualised three-dimensional design of each tooth preparation was completed using a full-crown preparation with CAD software developed in-house [9] as per the requirements of the cast metal full-crown preparation. The CAD three-dimensional data of isolated natural teeth before preparation were imported into a customised digital control software. The three-dimensional data of the tooth tissue to be removed was obtained using Boolean operations, and the single depth of ablation of the natural teeth was obtained. A total of 500 ablating layers was used for parametrising the settings in the digital control software in order to complete the discrete layered slices of the three-dimensional CAD model of the preparation. Scan-line filling and scan path planning were performed based on slice contour data, and the laser was selectively controlled on the tooth surface. A two-dimensional planar pattern of the layer was achieved by changing the direction of the high-speed two-dimensional galvanometer. The amount of convex lens advancement was set by a single depth of ablation, i.e. The laser parameters was set with the pulse energy of 300μj, a spot diameter of 38μm, and the scanning velocity 1900 mm s^{-1}, and the laser scanned five layers of pulses on the tooth surface to complete the ablation of the slice contour of the five layers. The convex lens advanced the amount of the single ablation depth, and a new round of slicing, scanning, and ablating was started. As accumulation continued, the desired three-dimensional shape of the tooth preparation was finally formed.

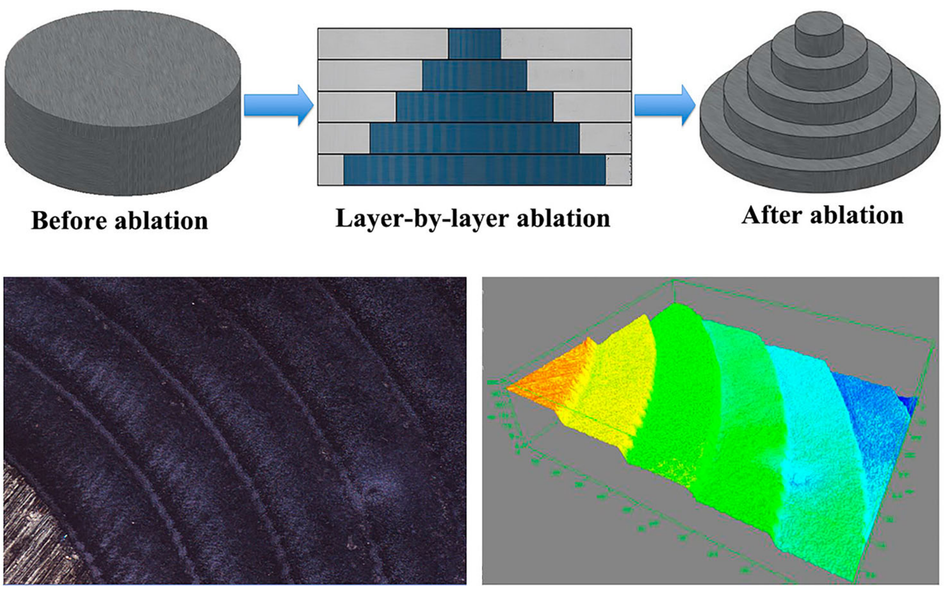

Figure 3. Path planning diagram for single depth of ablation determination and plot of ablating and measurement results.

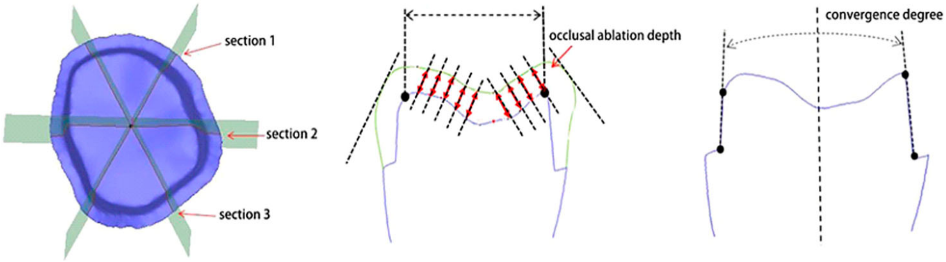

Figure 4. Schematic of software measurement method for thickness of occlusal surface preparation and occlusion convergence angle.

Software measurement and analysis

The three-dimensional data of the isolated natural teeth were automatically acquired using an intraoral scanner and imported into Geomagic Studio software together with the three-dimensional data of isolated crowns before preparation. The two sets of data were unified in the same coordinate system using a residual dentition common space registration method. The two sets of data were sectioned in three planes designed in different directions (the angle between two planes was 60°). The thickness of the occlusal surface preparation and the convergence angle of occlusion were measured using the software, and the mean and standard deviation were calculated using Statistical Product and Service Solutions (SPSS) 19.0 (Figure 4).

The three-dimensional data of the tooth preparation and the original design CAD data were simultaneously imported into Geomagic Studio software. The two sets of data were unified in the same coordinate system using a common space registration method. Overall evaluation and analysis of the automated tooth preparation was performed using Geomagic Qualify software.

Results

The preliminary single depth of ablation of the three-dimensional laser ablating of the natural tooth was 45 ± 3.55 μm. After simulation on the phantom head simulator, 15 full-crown natural tooth preparations with intact occlusal and axis surface morphology and smooth surfaces were created (Figure 5). Each process of isolated natural tooth preparation took an average of 17 ± 1.77 min.

Software measurement of the 15 isolated natural tooth preparations revealed that the occlusal depth were maximum value 2.130 mm, minimum value 2.060 mm, approximate mean 2.097 ± 0.022 mm, and approximate error 0.097 ± 0.022 mm, and convergence angle were maximum value 7.57 ± 0.208°, minimum value 6.53 ± 0.21°, approximate mean 6.98 ± 0.35°, and approximate error 0.98 ± 0.35°(Table 1). Compared to CAD data, the software analysis yielded an overall mean error of approximately 0.05–0.17 mm in the 15 isolated natural teeth preparations (Figure 6).

Discussion

A robot-controlled laser for automated tooth preparation is essentially control of the laser to achieve automated three-dimensional ablating of the crown of interest. According to the principle of three-dimensional laser ablating, the ideal three-dimensional object can be processed only by ensuring that the thickness of a single slice is equal to the actual depth of each laser ablating. Laser ablating is a non-contact forming and processing method. By adjusting the process parameters of the system, a single-pulse laser beam is used to etch the surface of the material to remove a certain volume of material, yielding a certain depth of ablation. Therefore, obtaining a suitable single depth of ablation is a prerequisite for ensuring three-dimensional laser ablating with high precision, efficiency, and quality.

Figure 5. Isolated natural tooth preparation after automated full-crown tooth preparation.

Table 1. Statistical description of occlusal surface preparation and convergence angle in 15 isolated natural tooth preparations.

	Thickness of occlusal surface preparation (mm)			Convergence angle (°)		
	Number	Mean	Standard deviation	Number	Mean	Standard deviation
1	10	2.120	.008	3	7.07	.15
2	10	2.080	.017	3	6.53	.21
3	10	2.130	.008	3	6.90	.26
4	10	2.060	.015	3	7.57	.21
5	10	2.090	.014	3	7.30	.36
6	10	2.085	.014	3	6.70	.20
7	10	2.100	.012	3	7.20	.36
8	10	2.107	.010	3	7.03	.25
9	10	2.097	.011	3	6.93	.35
10	10	2.100	.013	3	7.00	.26
11	10	2.088	.014	3	7.00	.26
12	10	2.077	.016	3	6.97	.31
13	10	2.092	.017	3	7.13	.25
14	10	2.127	.015	3	6.63	.31
15	10	2.094	.016	3	6.70	.36
Total	150	2.097	.022	45	6.98	.35

Note: The occlusal preparation thickness of the design model was 2000 μm, and the convergence angle was 6°.

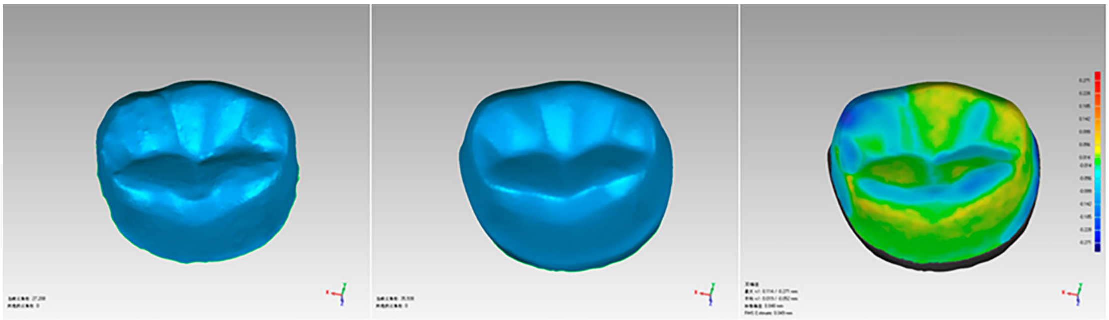

Figure 6. Software analysis of three-dimensional data of preliminary results and computer-aided design data of preparations.

In the present study, the automated preparation system yielded a single depth of ablation parameter through the grinding of the isolated natural tooth sample. The ultrashort pulse laser was controlled with specific parameters to complete the automatic full-crown natural tooth preparation at a single depth of ablation. The robotic automated control device must plan the movement path of the laser to complete three-dimensional tooth grinding, select the appropriate ablating mode, and plan the precise control path to improve ablating efficiency. The initial design of the experiment used two tooth preparation methods: layer ablating and stripping. The stripping method can reduce the amount of tooth tissue removal during the tooth preparation process, thereby improving the efficiency of automated tooth preparation. However, this method is more complicated than the layer ablating method because of the light blocking during the ablating process, which makes path planning more complicated. Therefore, the layer ablating method was the first choice to complete the entire automated tooth preparation process in this experiment.

The results of this experiment show that robotic automated tooth preparation is superior to manual tooth preparation as reported in the literature with respect to efficiency and accuracy of ablating [9,10]. In order to accelerate and improve clinical application of the tooth preparation robot, it is necessary to further improve the overall performance of the system. The next step is to conduct more in-depth research on ablating efficiency, ablating range, and safety. With respect to ablating efficiency, light blocking issue in the stripping tooth preparation method has not yet been solved. Furthermore, different laser control parameters, such as surface scanning speed and energy density, can affect ablating efficiency [11], and it is necessary to investigate the efficiency of ablating hard dental tissue with ultrashort pulse lasers having different energy densities. With respect to ablating range, it is currently limited to shoulder-less full-crown tooth preparations. The scope is limited, and shouldered automated full-crown tooth preparations and various complex morphologies in the oral cavity, including different cavity preparations for dental caries, inlays, veneers, partial crowns, and dental implant cavities, remain to be investigated. With respect to safety, the current safety policy of the system has not yet been perfected, and it is impossible to achieve visualisation and intelligent control. These problems and limitations can be the focus of further research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by the National Natural Science Foundation of China (grant number 81571023), the Clinical Medicine Plus X - Young Scholars Project of Peking University (grant number PKU2019LCXQ024), and the University of Science & Technology Beijing (grant number 2018-Z04).

References

[1] Feng HL, Xu J. Prosthodontics. 2nd ed. Beijing: Peking University Medical Press; 2013.

[2] Theodoroff SM, Folmer RL. Hearing loss associated with long-term exposure to high-speed dental handpieces [J]. Gen Dent. 2015;63(3):71–76. PMID: 25945769.

[3] Yamada T, Kuwano S, Ebisu S, et al. Statistical analysis for subjective and objective evaluations of dental drill sounds. Plos One. 2016;11(7):e0159926. doi:10.1371/journal.pone.0159926. PMID: 27462903.

[4] Willershausen B, Callaway A, Wolf TG, et al. Hearing assessment in dental practitioners and other academic professionals from an urban setting. Head Face Med. 2014;10:1–7. doi:10.1186/1746-160X-10-1. PMID: 24438539.

[5] Sun J, Xin XZ, Zhang FQ. Noise level in prosthetic practice caused by dental handpieces[J]. Chin J Prosthodonti. 2010;11(1):2–4. doi:10.3969/j.issn.1009-3761.2010.01.002.

[6] Raucci-Neto W, Raquel Dos Santos C, Augusto de Lima F, et al. Thermal effects and morphological aspects of varying Er:YAG laser energy on demineralized dentin removal: an in vitro study. Lasers Med Sci. 2015;30(4):1231–1236. doi:10.1007/s10103-014-1579-3. PMID: 24756325.

[7] Melo MA, Lima JP, Passos VF, et al. The influence of dentin demineralization on morphological features of cavities using Er:YAG laser. Photomed Laser Surg. 2015;33(1):22–28. doi:10.1089/pho.2014.3758. PMID: 25554858.

[8] Al-Batayneh OB, Seow WK, Walsh LJ. Assessment of Er:YAG laser for cavity preparation in primary and permanent teeth: a scanning electron microscopy and thermographic study. Pediatr Dent. 2014;36(3):90–94. PMID: 24960377.

[9] Aminian A, Brunton PA. A comparison of the depths produced using three different tooth preparation techniques. J Prosthet Dent. 2003;89:19–22.

[10] Leempoel PJB, Lcnmens LM, Snook PA, et al. The convergence angle of tooth preparations for complete crowns. J Prosthet Dent. 1987;58(4):414–416.

[11] Schelle F, Polz S, Haloui H, et al. Ultrashort pulsed laser (USPL) application in dentistry: basic investigations of ablation rates and thresholds on oral hard tissue and restorative materials. Lasers Med Sci. 2014;29(6):1775–1783. doi:10.1007/s10103-013-1315-4. PMID: 23609558.