Effectiveness of an actuator-driven pulsed water jet for removal of softened carious dentin

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The aim of this study was to assess the utility of an actuator-driven pulsed water jet (ADPJ) as a hardness-dependent carious dentin removal device by using different outputs. Thirty-six plane surface dental caries samples were treated with the ADPJ at 150, 200, and 250 voltage (12 teeth each). The Knoop hardness number (KHN) and Ca/P mass ratio were measured at 70 μm from the deepest point of the removing groove. Furthermore, three other teeth samples were manually treated with the ADPJ at the three above mentioned voltages (one tooth each) for 1 min. The KHN and Ca/P mass ratio were measured at 70 μm from the surface of the residual dentin part. In both the KHN and Ca/P mass ratio, higher residual dentin depended on the applied voltage of ADPJ. The ADPJ enabled the removal of softened carious dentin in an applied voltage-dependent manner.

Keywords: Actuator-driven pulsed water jet (ADPJ), Carious dentin, Knoop hardness number (KHN)

INTRODUCTION

In dental treatment, minimal intervention is important to preserve the tooth structure and includes the selective removal of softened carious dentin1). Sano2) reported a Knoop hardness number (KHN)<20 in a bacterially infected area in active carious lesions, as determined from in vitro histological experiments using an optical microscope. Based on that report, the caries treatment guidelines published by the Japanese Society of Conservative Dentistry described the hardness of carious dentin to be removed as 20 KHN3). To remove softened carious dentin, steel round burs and hand excavators are mainly employed4,5). However, removing softened carious dentin while measuring KHN is impossible, so the evaluation of the hardness of the carious dentin depends on the dentist feeling it with the fingers. Despite the introduction of acid red propylene glycol solution (caries detector6) as an asset to the understanding of caries and development of caries removal techniques6), dye applications are an adjunctive clinical procedure useful in caries treatment, never an objective indicator7). This is because it allows caries removal based on visual examination, which can result in excessive removal of healthy tooth substance. Therefore, a device enabling objective hardness-dependent removal of softened carious dentin would improve caries treatment.

The actuator-driven pulsed water jet (ADPJ) is an emerging technology with remarkably reduced water consumption and the ability to selectively remove tissues based on their material stiffness8). The ADPJ enables soft tumor excision with preservation of the nerves and blood vessels9). In the field of neurosurgery, it has already been applied in brain tumor surgery as a substitute for scalps10,11). We previously developed an ADPJ for dental use (maximum applied voltage, 240 V) with a higher output than that of the previous pulse jet (maximum operating voltage, 140 V) used in the medical field and reported that the effect of removing dental calculus increases depending on the applied voltage, without damaging tooth surfaces12). Therefore, the null hypothesis in this study was that a higher output of ADPJ could remove harder carious dentin without damaging the sound dentin. Based on the above, the present study aimed to assess the utility of the ADPJ as a hardness-dependent carious dentin removal device.

MATERIALS AND METHODS

ADPJ system

The ADPJ system was described in detail in our previous study10,12). Figure 1 shows a photograph (Fig. 1a) of the piezo-driven pulse jet’s handpiece and a schematic diagram of its internal structure (Fig. 1b). The ADPJ system is composed of a pump chamber driven by a piezo actuator, a stainless-steel tube (Connection Pipe), and a nozzle with an internal diameter of 0.15 mm. Sterilized water is continuously fed into a chamber by the supply pump through a capillary inlet at a 17.8 mL/min flow rate. The water jet from the nozzle is injected as a high-speed (approximately 100 m/s) jet by the movement of the piezo and intermittently injected as a pulse jet split.
The ADPJ is generated by the movement of the piston driven, and water is intermittently released through the chamber. Water volume and speed are controlled with a manual switch. Dissected tissue, splashing, and excess liquid are aspirated through the suction pipe.

Fig. 2 Flat caries sample using ADPJ treatment.
(a) Microscopic images before ADPJ treatment. (b) ADPJ treatment photograph. The white arrow shows the direction of movement. (c) Microscopic images after ADPJ treatment. The black arrowhead shows the removing groove. The white dotted line shows the cut line. (d) Microscopic sample images to evaluate residual dentin. The white arrowhead shows the deepest part of the removing groove.

Ethical aspects and registration
This study was performed in accordance with the Declaration of Helsinki. This study was approved by the Ethics Committee of the Faculty of Dentistry, Graduate School of Dentistry, Tohoku University (registration number 2017-3-24). Written informed consent was obtained from each patient for the use of their extracted teeth diagnosed as unpreservable in this experiment. For patients under 18 years of age, informed consent was also obtained from their parents.

ADPJ treatment on a plane surface dental sample
1. Sample preparation
This study utilized 36 extracted human permanent teeth (upper and lower premolars and molars) with diagnosed caries in the dentin but not extending to the dental pulp and for which conservative treatment was impossible due to periodontal disease. Those were fixed in 0.1% glutaraldehyde solution (Fuji Film Wako Pure Chemical Industries, Osaka, Japan) by immersion for 1–3 weeks13,14. The teeth were then embedded in orthodontic resin (Splint Retainer Resin, GC, Tokyo, Japan) in a water bath (55°C temperature) at 2 atm. The embedded samples were cut parallel to the tooth axis using a microtome (Low Speed Diamond Wheel Saw, South Bay Technology, San Clemente, CA, USA) at 300 rpm speed using a diamond wheel (DWH4122-wheel, Meiwafo machinery Co., Ltd., Tokyo, Japan) at the central portion of dental caries (Fig. 2a). The cut surfaces were precisely polished by silicon carbide (EAGLE Brand Waterproof Abrasive Paper P2000/P2500, Kovacs, Tokyo, Japan) and polishing film (3M lapping film sheet # 4000, 3M Japan Products, Tokyo, Japan). Next, the samples were rinsed with flowing water for 10 s and cleaned with distilled water using an ultrasonic cleaner bath (MCS-2, AS ONE, Osaka, Japan) for 10 min.

The caries sample was attached to the stage and the nozzle, at an applied voltage of 150, 200, and 250 V (12
teeth each, total 36 teeth), was placed 1.5 mm away from the caries sample surface (Fig. 2b). Subsequently, each fixed caries sample was moved at a speed of 0.01 mm/s (white arrow in Figs. 2a, b).

2. Evaluation of the effectiveness of removal of dental caries

Three-dimensional images were acquired with a One Shot 3D Microscope (VR-3000, KEYENCE, Osaka, Japan), and the groove depth formed by the removal of the caries was measured (Fig. 2c).

After the sample was re-embedded in orthodontic resin, using the data of the One Shot 3D Microscope as reference, the sample was cut perpendicular to the deepest part of the removing groove (white dotted line in Fig. 2c) to evaluate the residual dentin at the deepest point (white arrowhead in Fig. 2d). After that, KHN was measured at a site 70 μm from the deepest one point of the removing groove by application of a 0.45 N (25 gf) load for 15 s by means of a micro-hardness testing machine (HM-221, Mitutoyo, Kanagawa, Japan).

The dentin surface was polished again using silicon carbide and ultra-precision finishing polishing film. Thereafter, it was washed with running water for 10 s and cleaned with distilled water using an ultrasonic cleaner bath, and then dried at room temperature for one week. The polished samples were coated with carbon using vacuum deposition equipment. Dentin parts 70 μm away from the deepest point of the removing groove were observed and qualitatively and quantitatively analyzed using a scanning electron microscope (SEM) with energy dispersive X-ray spectrometry (EDX; SM-6390LA, JEOL, Tokyo, Japan). Element mapping conditions were an accelerating voltage of 20 kV, a working distance of 10 mm, and a pixel count of 512×384 pixels in an area of 300×400 μm. The calcium to phosphorus mass ratio (Ca/P mass ratios) was calculated by point analysis.

**ADPJ treatment for a single point on a plane sound dentin surface**

One extracted non carious premolar tooth diagnosed as suffering from periodontal disease was used. In the same manner as caries samples mentioned above, a resin was embedded and the tooth was cut parallel to the root (Fig. 3a). After the KHN was measured by application of a 0.45 N (25 gf) load for 15 s, the sample was attached to the stage. The nozzle at an applied voltage of 250 V was placed 1.5 mm away from the sample's surface, and ADPJ was continuously applied to a single point 100 μm from the point of KHN measurement for 30 s. After ADPJ treatment, the surface of the sample was evaluated under an optical microscope (TG500PC, Shodensha, Osaka, Japan).

**Manual ADPJ treatment of dental caries**

1. Sample preparation

Three extracted permanent upper premolar caries teeth were fixed in 0.1% glutaraldehyde solution by immersion for 1–3 weeks. Each tooth was held in hand and was manually removed by moving the tip of the nozzle along with the outline form of the caries cavity with the ADPJ at 150, 200, 250 V (one tooth each) for 1 min, and then, each tooth embedded in orthodontic resin (Figs. 4a, b, c). The embedded samples were cut parallel to the tooth axis using a microtome at the central portion of dental caries (white dotted line in Fig. 4b).

**Evaluation of the effectiveness of removal of dental caries**

KHN was evaluated at 12 points of the residual dentin, 70 μm away from the site from which caries was removed.
by the ADPJ, and at 100 μm intervals from each other by application of a 0.45 N (25 gf) load for 15 s. The Ca/P mass ratio of the same part was measured (white arrowhead in Fig. 4c).

**Statistical analysis**
Differences in tooth groove depth, residual dentin KHN, and Ca/P mass ratio of the residual dentin were tested using ANOVA with the Tukey-Kramer HSD test. All statistical analyses were performed using statistical analysis software (JMP Pro15, SAS Institute Japan, Tokyo, Japan), and \( p<0.05 \) was set as the level of statistical significance.

**RESULTS**

*Effectiveness for plane surface samples*
Figure 5a shows the representative plot data for each voltage removal depth. The plots of 150 V and 200 V demonstrate shallow and gradual plots, respectively. In contrast, the plot of 250 V reveals a deep and sharp plot. As shown in Fig. 5b, the removal depth was 0.13 (±0.12) mm at 150 V, 0.22 (±0.21) mm at 200 V, and 0.52 (±0.64) mm at 250 V. The removal groove depth was statistically significant between 150 and 250 V (\( p=0.0405 \)); however, no significant differences were noted between 150 and 200 V (\( p=0.8399 \)) and between 200 and 250 V (\( p=0.1336 \)).

As shown in Fig. 6a, KHN at 150, 200, and 250 V was 9.79 (±3.17), 15.1 (±3.65), and 18.2 (±3.29), respectively. ADPJ treatment at 150 V resulted in significantly lower hardness than that at 200 V (\( p=0.0008 \) and 250 V (\( p<0.0001 \)); however, no significant differences were noted between 200 and 250 V (\( p=0.063 \)). Figure 6b shows the relationship between the applied voltage and the Ca/P mass ratio. The Ca/P mass ratio was 1.05 (±0.19) at 150 V, 1.33 (±0.26) at 200 V, and 1.80 (±0.55) at 250 V. The Ca/P mass ratio at 250 V was significantly higher than that at 150 V (\( p<0.0001 \)) and 200 V (\( p=0.0092 \)).

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**Fig. 5** Removal depth of the flat caries sample.
(a) Groove depth plot at various voltages, (b) Groove depth. Difference with respect to the applied voltage: *\( p<0.05 \)

**Fig. 6** Residual dentin substance of a flat caries sample.
(a) KHN, (b) Ca/P mass ratio: Difference with respect to the applied voltage: *\( p<0.05 \)
however, no significant differences were noted between 150 and 200 V ($p=0.1685$).

Regarding the sound dentin sample for which the Knoop hardness was 67 KHN, no scratches or dents could be found, which was similar to that before ADPJ treatment (Fig. 3b).

Manual removal of caries with ADPJ

Representative microscopic images of the dental caries before and after ADPJ treatment at 250 V are shown in Fig. 4. These images show that softened carious dentin has been removed after the treatment. The residual dentin KHN at 150, 200, and 250 V was 20.8 (±7.85), 24.5 (±9.81), and 44.0 (±17.4), respectively (Fig. 7a). As shown in Fig. 7b, the residual dentin Ca/P mass ratio was 1.46 (±0.16) at 150 V, 1.47 (±0.19) at 200 V, and 1.67 (±0.21) at 250 V. With respect to both KHN and the Ca/P mass ratio, ADPJ treatment at 250 V was significantly better than that at 150 and 200 V (KHN; 150 V vs. 250 V, $p=0.0002$; 200 V vs. 250 V, $p=0.0015$; Ca/P mass ratio: 150 V vs. 250 V, $p=0.0215$; 200 V vs. 250 V, $p=0.0281$); however, no significant differences were noted between 150 and 200 V (KHN: $p=0.744$, Ca/P mass ratio: $p=0.9931$).

DISCUSSION

The ADPJ could be advantageous for selective grinding of structures of arbitrary hardness just by changing the applied voltage, with a commensurate removal effect using a small amount of water due to the discontinuous water flow$^{12,16}$. In addition, the characteristics of water jet system hardly produce heat or result in deformation, strain, or residual stress on the material$^{16}$. Based on these characteristics, the ADPJ might enable the removal of softened dentin with low irritation to the residual tooth and dental pulp. As an alternative to conventional mechanical techniques such as steel round burs or hand excavators, which uses impact pressure for caries removal, the air abrasion technique has been introduced. Honda et al.$^{17}$ in particular, visually evaluated removal of carious dentin using the cylinder-type nozzle and two sizes of the bugle-type nozzle (0.6-1.0 nozzle and 0.8-1.2 nozzle) each on four teeth, and showed that the bugle-type nozzles were favorable for the removal of carious dentin. However, air abrasion cannot be used for all patients, such as in cases of severe dust allergy, asthma, chronic obstructive lung disease, recent extraction or other oral surgery, open wounds, advanced periodontal disease, recent placement of orthodontic appliances and oral abrasions, or subgingival caries removal$^{18}$. We endeavor to develop the ADPJ as a safer device that uses only water.

The primary aim of cavity preparation in a carious tooth is to remove infected dentin$^{19}$. It was reported that initial samples from soft and wet lesions harbored significantly more bacteria, including *Lactobacilli* and *Streptococcus mutans*, than samples from medium, hard, or dry lesions$^{20}$, and that infected dentin is decalcified, softened, and devoid of its remineralization ability$^{5,19-23}$. With respect to the evaluation of carious dentin, previous studies used the KHN as a measure of softened dentin hardness and Ca/P mass ratio as one of the mineral components$^{2,3,11,15,24-26}$. Therefore, we evaluated the qualitative relationship between the applied voltage and residual dentin in constant-speed moving injection measuring KHN (see Fig. 5a) and Ca/P mass ratio at the deepest part of the removing groove (see Fig. 5b). For both KHN and Ca/P mass ratio, higher residual dentin correlated with higher applied ADPJ voltage, indicating that harder and less demineralization dentin could be efficiently removed by a higher applied voltage. For the sound dentin in our study, no damage could be seen even after 30 s of continuous ADPJ treatment to the single point (see Fig. 3b). Our results supported our null hypothesis (see Introduction) that a higher output of ADPJ could remove harder carious dentin without damaging the sound dentin and demonstrated that the
effectiveness of carious dentin removal by the ADPJ at a constant jet pressure depends on the applied voltage. As for manual treatment with the ADPJ (see Fig. 7), using an applied voltage of 150 V was 7 out of 12 points higher, that of 200 V was 8 points higher, and that of 250 V was 10 points higher in comparison to using the removal threshold of 20 KHN recommended by the Japanese Society of Conservative Dentistry based on Sano’s report[2]. These results suggest that softened dentin might be effectively removed with the ADPJ at an applied voltage of 250 V.

There are some limitations to this study. The effects during and after ADPJ treatment on the dental pulp in caries close to the dental pulp or on the apical periodontal tissues in cases with exposed dental pulp cavity remain unknown. In some cases (e.g., subgingival caries), high-voltage ADPJ may be used for the removal of softened carious dentin adjacent to soft tissues. It is also necessary to consider the length and shape of the nozzle that is suitable for oral use. Additional safety evaluations in animal experiments are required, where the direct observation of tissue damage (i.e., bleeding or inflammation) can inform the readjustment of the applied voltage, frequency, and water volume. In addition, further studies with many extracted carious teeth inserted in various parts of the jaw phantom are needed to investigate suitable nozzle configurations and sizes for manual ADPJ treatment of oral cavities.

CONCLUSION
To develop a hardness-dependent removal device for carious dentin, we examined the hardness and Ca/P ratio of the residual dentin after high-applied voltage ADPJ treatment of carious dentin. The results in this study demonstrated that the ADPJ system enables the removal of softened and decalcified carious dentin in a hardness-dependent manner.

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