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Effects of Bleaching Gel with a Neutral pH and Nonthermal Plasma (Electric Currents and Magnetic Fields) on Dental Hard Tissues

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Tooth bleaching gel, that comes in direct contact with the tooth surface for a long time, affects hard dental tissue. Nonthermal plasma consists electrons, ions, charged particles, electric filed and magnetic field. The motion of an electrically charged particle such as electron and ion can generate both electric and magnetic field. This study was conducted to investigate how tooth bleaching with 15 % hydrogen peroxide (HP) and plasma (from electric currents and magnetic fields) affects hard dental tissue. Extracted human teeth were treated with 15 % HP, with and without plasma. We fabricated a 15 % HP gel with neutral pH, and applied the gel and plasma to tooth surfaces for 30 minutes. The overall color change following 15 % HP gel and plasma was higher than in the other groups, and there were no significant changes in microhardness or mineral contents. Application of 15 % HP and plasma showed a bleaching high effect, with no damage to hard dental tissue. Even though 15 % HP has adverse effects, results can be effective without danger if treatment times are kept short.

Keywords : nonthermal plasma, electric currents, magnetic fields, tooth bleaching, safety, neutral pH

1. Introduction

Tooth bleaching has become popular in aesthetic dentistry since the introduction of the nightguard vital bleaching technique by Haywood and Heymann [1]. Tooth bleaching is divided into two methods: office bleaching, which requires the application of a high concentration of hydrogen peroxide (HP, 30 %) and a light source [2], and home bleaching, which is carried out for several weeks outside the dental clinic using a mouthguard made by the dentist and a lower concentration of HP (2-10 %) [3-6].

Most bleaching agents contain HP and carbamide peroxide as activators. HP has been widely used in various concentrations compared to carbamide peroxide. It also has a dramatic bleaching effect at high concentrations (30-35 %) with UV light or laser radiation (electron magnetic wave) in the dental clinic [2, 7]. However, many problems have been caused by high concentrations of bleaching agent, such as gingival irritation, tooth sensitivity, pulp damage, tooth demineralization, and decreased enamel hardness [8-14]. Thus, the aim of the present study was to minimize the side effects of bleaching agent by reducing contact time with the tooth surface.

Plasma (magnetic fields) is produced from electric currents and magnetic fields. It is the fourth state of matter, and has attracted much attention in biomedicine owing to its potential function. Many types of nonthermal plasma devices have been developed [15]; Lee *et al.* [16] showed the effect of tooth bleaching using nonthermal plasma and HP. Furthermore, many previous studies have reported the bleaching effect of various plasma-based bleaching methods; Nam *et al.* [17] reported that tooth bleaching using non-thermal plasma had a better bleaching effect than other light sources, and maintained a stable 37 °C tooth surface temperature. There is a demand for cosmetically attractive smiles and whiter teeth. Bleaching effects should be quick, certain, and long-lasting. Non-thermal plasma can increase the bleaching effect rapidly, and combined with 15 % HP, can provide high long-lasting stability.

The aim of the present study was to assess the speed of

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a new combined tooth bleaching method containing 15 % HP and non-thermal plasma on teeth with minimal treatment.

2. Materials and Methods

2.1. Plasma device

Figure 1 shows the pen-type plasma (magnetic fields) device that was used in this study, driven by a low-frequency high voltage (6 V). Helium gas with a flow rate of 2 L·min^{-1} is fed for operating the device at atmospheric pressure in air. Application of sufficient electrical power changes He gas into a partially ionized gas called plasma.

The governing equations for non-isothermal gas flow are given in the following fluid equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p - \nabla \cdot (\boldsymbol{\tau}) + \mathbf{f} \tag{2}$$

$$\boldsymbol{\tau} = -\mu(\nabla \mathbf{v} + (\nabla \mathbf{v})^T) - \frac{2}{3}(\nabla \cdot \mathbf{v})\mathbf{I} \tag{3}$$

Here, r, $\mathbf{v}$, p, and μ are the density, average velocity, pressure, and molecular viscosity, respectively. $\boldsymbol{I}$ is the unit matrix, and t is the time. The second term on the right-hand side of the equation (3) describes the volume dilation effect, where $\mathbf{f}$ is the net force per unit volume. In addition to these equations, energy conservation is included in a conventional form. The governing equations for the charged particles and radicals were obtained from the Boltzmann equation.

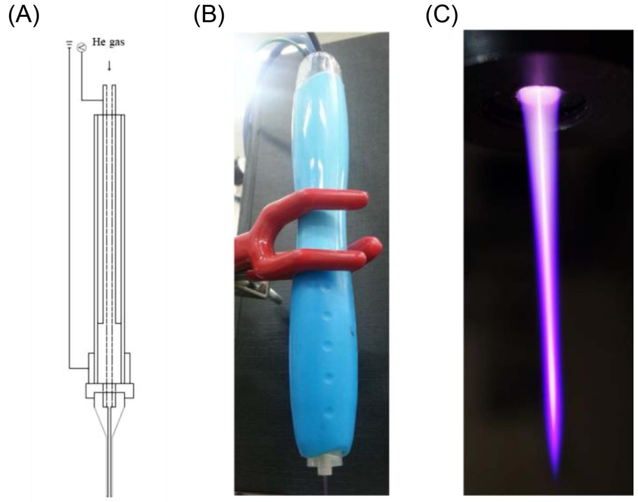

Fig. 1. (Color online) Tooth bleaching with nonthermal plasma. (A) Schematic drawing of plasma device. (B) Photograph of operated device. (C) Ionized plasma under the action of the magnetic field.

The governing equations for the considered discharge system were derived from the moments of the Boltzmann equation, called the plasma fluid model [17]. The zeroth moment equation is called the continuity equation, which is as follows:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot J_e = R_e \tag{4}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot J_p = R_p \tag{5}$$

$$\frac{\partial n_q}{\partial t} + \nabla \cdot J_q = R_q \tag{6}$$

where n_e, n_p, and n_q are the electron density, positive ion density, and negative ion density, and J_e, J_p, and J_q are the electron flux, positive ion flux, and negative ion flux, respectively. R_e, R_p, and R_q are denoted for the electron production or loss terms, positive ions, and negative ions, respectively, which are related to volumetric reactions such as ionization, recombination, and excitation. The subscripts e, p, and q stand for electron, positive ion, and negative ion, respectively. The fluxes are derived by the first moment of the Boltzmann equation. In particular, in an atmospheric pressure discharge, the drift-diffusion approximation is adopted to simplify J_e, J_p, and J_q as follows due to the atmospheric pressure condition:

$$J_e = -D_e \nabla n_e + \mu_e n_e \nabla \phi \tag{7}$$

$$J_p = -D_p \nabla n_p - \mu_p n_p \nabla \phi \tag{8}$$

$$J_q = -D_q \nabla n_q + \mu_q n_q \nabla \phi \tag{9}$$

where, μ and D are the mobility and diffusion coefficients, respectively. Finally, the electron magnetic energy balance was obtained by:

$$\frac{\partial (n_e \varepsilon)}{\partial t} + \nabla \cdot \left[\frac{5}{3} n_e \varepsilon \mathbf{v}_e - \frac{5}{3} n_e D_e \nabla \varepsilon \right] = -eJ_e \cdot E - n_e N k_L(\varepsilon) \tag{10}$$

where ε, v_e, N, E, and k_L are the electron magnetic energy, electron velocity, neutral density, electric field, and collision rate for loss of electron magnetic energy, respectively. The production rates in Eqs. (4) to (6), and the collision reaction rate of electrons in Eq. (10), can be obtained by references for atmospheric pressure plasma discharges [18]. Finally, the electric field is calculated from the negative gradient of the electric potential ϕ, which is calculated from the Poisson's equation, where ε_0 is the permittivity of free space, and e is the electron charge:

Table 1. Ingredients of dental bleaching gel.

Ingredient	Function
Hydrogen peroxide	Active oxidant
D-Sorbitol	Humectant
Cabopol 940	Emulsion stabilization
Glycerine	Humectant
Propylene glycol	Humectant
Sodium hydroxide (0.5 M)	Neutralization

$$\nabla^2\phi = \frac{e}{\varepsilon_0}(n_p - n_e - n_q) \tag{11}$$

2.2. Fabrication of 15 % HP gel

The ingredients of the 15 % HP gel are shown in Table 1. Laboratory bleaching gel was mixed, as a neutral pH gel, at about 6 ºC, and placed inside a syringe for use in the study experiment.

2.3. Tooth preparation and experimental bleaching procedure

The study was approved by the Kangwon National University (KNU) Institutional Review Board (KWNUIRB-2019-02-005-001). Fifty extracted teeth were selected and used in this study, except those with caries, cracks, fractures, and erosions. The samples were thoroughly polished with an ultrasonic scalar to remove any calculus and periodontal remnants, and were polished with a rubber cup and pumice. Each tooth was cut from its crown at the cementoenamel junction using a low-speed saw (Minitom, Struers, Copenhagen, Denmark). The specimens were made with a 3 × 3 × 2 mm block for color change and 1 × 2 × 1 mm slab for microhardness, and mineral contents. The specimens were randomly divided into two groups.

Each tooth specimen was dried before the bleaching gel was applied. For group 1, 15 % HP gel was applied to the surface of the enamel for 30 minutes. For group 2, 15 % HP gel and plasma that had been treated for 30 minutes were applied to the surface of the enamel. The specimens were subjected to color measurement and re-application of the bleaching gel every 10 minutes to prevent the bleaching gel and teeth from being affected by the heat generated from the plasma. Subsequently, the teeth were cleaned with sterile distilled water and dried in preparation for microscopic photography. Thereafter, the specimens were kept at room temperature in artificial saliva. Changes in the tooth color was observed after 24 hours.

2.4. Assessment of tooth color

Image of each tooth specimen were captured with a digital camera (Pixel Link PL-B686CU, Canada) connected to a stereomicroscope (40x magnification, SZ-CTV, Olympus, Tokyo, Japan) and processed using Image-Pro Plus 5.1 software (Media Cybernetics, Inc., DC, USA). The color change of each tooth was observed before and after treatment. Assessment of the color change was based on the Comission International de L'Eclairage Lab (CIELAB) Color System, which is the international standard. ΔL^*, Δa^*, and Δb^* represent the changes to lightness-darkness, redness-greenness, and yellowness-blueness parameters, respectively, and overall color changes were calculated with respect to baseline color parameters.

2.5. Mineral analysis

Elements were measured with an electro micro analyzer (EPMA; SX100, CAMECA, Corbevoie, France) to determine the quantitative changes in the enamel and dentin slab. The specimens were coated with carbon, which was detected under 10 um, and had a 15 keV accelerating voltage and a 20 nA electric beam current. The detected values were calculated to have an average weight % of 4 points per specimen.

2.6. Measurement of microhardness

Microhardness was measured using Vikers hard testing (microhardness, Akashi MWK-III, Tokyo, Japan) at a 100 g load applied for 10 s. Specimens were assessed five times using a microscope with 400x magnification. The average values were calculated as means and standard deviations per group.

2.7. Statistical analysis

The difference in color changes between the control and experimental groups was tested via t-tests and ANOVA with a 95 % significance level, using SPSS (Version 18, SPSS, Chicago, IL, USA). The means and standard deviations of all the specimens in each group were calculated.

3. Results

3.1. Effect of tooth bleaching

The color changes of the surface of the enamel are shown in Fig. 2. The ΔE value in the group that was treated for 30 minutes with 15 % HP gel and plasma was 15.58 ± 2.47, and was higher than in the group treated with 15 % HP only. After 24 hours, the ΔE value in the group that was treated with 15 % HP gel and plasma was still higher than in the group treated with 15 % HP only. Thus, a significant color change was seen in the experimental group in this study, compared to the control group.

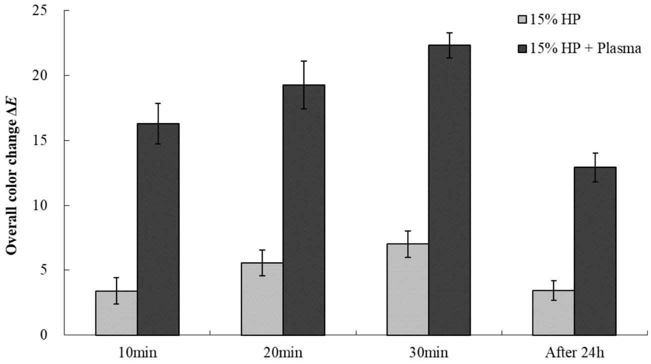

Fig. 2. Overall color changes of 15 % HP and 15 % HP with plasma. Bleaching generally led to a significant color change in the experimental group compared to the other groups ($p > 0.05$).

Table 2. Mean ± SD Vickers hardness values and results of one-way analysis of variance.

Division	Bleaching agent	Mean values ± SD	ANOVA p-value
Enamel	Control	383.01±19.29	0.383
	15% HP	368±21.09	
	15% HP + Plasma	369.63±14.04	
Dentin	Control	93.01±3.57	0.762
	15% HP	91.88±9.26	
	15% HP + Plasma	89.10±1.54	

Table 3. Mean ± standard deviation mineral contents of the enamel surface after bleaching, and statistical results of one-way analysis of variance.

Division	Contents	Bleaching agent	Mean values ± SD	ANOVA p-value
Enamel	Na	Control	0.72±0.06	0.772
		15% HP	0.71±0.11	
		5% HP + Plasma	0.71±0.06	
	P	Control	16.71±0.39	0.394
		15% HP	16.63±0.29	
		5% HP + Plasma	16.57±0.12	
	Mg	Control	0.17±0.03	0.316
		15% HP	0.17±0.02	
		5% HP + Plasma	0.17±0.03	
	Cl	Control	0.03±0.04	0.685
		15% HP	0.30±0.02	
		5% HP + Plasma	0.30±0.05	
	Ca	Control	35.67±0.41	0.708
		15% HP	35.05±0.43	
		5% HP + Plasma	35.05±0.17	
	Zn	Control	0.02±0.01	0.283
		15% HP	0.02±0.01	
		5% HP + Plasma	0.02±0.01	

Table 4. Mean ± standard deviation mineral contents of the dentin surface after bleaching, and statistical results of one-way analysis of variance.

Division	Contents	Bleaching agent	Mean values ± SD	ANOVA p-value
Dentin	Na	Control	0.57±0.04	0.880
		15% HP	0.57±0.04	
		5% HP + Plasma	0.57±0.06	
	P	Control	14.92±0.58	0.799
		15% HP	14.67±1.03	
		5% HP + Plasma	14.46±0.67	
	Mg	Control	0.65±0.06	0.083
		15% HP	0.45±0.08	
		5% HP + Plasma	0.61±0.09	
	Cl	Control	0.05±0.01	0.377
		15% HP	0.04±0.01	
		5% HP + Plasma	0.03±0.01	
	Ca	Control	31.06±0.45	0.756
		15% HP	30.93±0.50	
		5% HP + Plasma	29.83±0.34	
	Zn	Control	0.02±0.01	0.582
		15% HP	0.02±0.01	
		5% HP + Plasma	0.02±0.01	

3.2. Change in microhardness value

The results of the measurement of surface microhardness after treatment with 15 % HP with and without plasma are shown in Table 2. There was no significant difference ($p > 0.05$) between the control group (15 % HP only) and experimental group (15 % HP with plasma) with regard to microhardness of enamel and dentin. All the Vickers microhardness numbers were at a similar level.

3.3. Changes in mineral contents

Calcium, phosphorus, natrium, chlorine, zinc, and magnesium values are shown in Table 3 and 4. The values in the control and experimental groups were not significantly different; the group that was treated with 15 % HP and plasma had a rate comparable to the group treated with 15 % HP only. The table shows that there were no differences in the values of all minerals between the two groups. ANOVA revealed no significant differences between bleached and non-bleached teeth.

4. Discussion

Tooth bleaching, which is currently widely performed, has both advantages and disadvantages. In-office bleaching using high concentration HP causes problems, whereas at-home bleaching using low concentration HP is ineffective. Nevertheless, many tooth bleaching studies using plasma provide a variety of therapeutic procedures [1, 17, 19-22], and can be active in the stagnant bleaching market.

The plasma (magnetic fields) device used in this study had a low frequency, and was the same as that used in a previous study by Nam *et al.* [22]. The difference with this previous device, however, was the absence of Teflon that acts as a dielectric barrier and gas path; this device is also aesthetically advantageous for a pen-type plasma device.

To evaluate the effect of tooth bleaching, tooth color was measured using the traditional method. There are two tooth color measurement methods: the vitapan shade guide, which is reflected in the subjective assessment of tooth color by the inspector, and the CIELAB color system, which is widely applied as an international standard for tooth color measurement [23, 24]. This study used the CIELAB color system to evaluate tooth color as it is more objective.

Tooth bleaching using fabricated 15 % HP gel and plasma was performed for 30 minutes, and led to significant increases in tooth color. Thus, this bleaching method showed high efficacy within a short time. Sulieman *et al* [25] examined the effects of various HP concentrations; when the tooth specimen was treated with 15 % HP for 8 hours, the tooth color change value via electronic chromometer was 16.41. However, Jie *et al.* [26] reported that the combination of plasma with low concentration HP (6 %) achieved an excellent bleaching effect compared to high concentration HP (35 %) without a plasma.

Many studies have been conducted to explore the effect of tooth bleaching on hard dental tissue, but the results have been highly controversial. Several previous studies have shown that bleaching agents have a destructive effect on hard dental tissue, and cause changes in the enamel components and morphology, as well to microhardness [27-29]. Furthermore, many studies estimated the involvement of various concentrations of HP in the decrease in microhardness [30-32]. Some studies showed tooth mineral loss after peroxide-based bleaching [33, 34]. The present study showed that a novel tooth bleaching method does not damage hard dental tissue. We fabricated gel with a neutral pH level, which is good for the teeth, as the pH value of bleaching gel can reduce any adverse alkaline effects [29].

The time that the tooth surface is in direct contact with high concentration of HP is key. Therefore, a new protocol of plasma tooth bleaching is sure to replace the existing methods. It would be ideal to combine 15 % HP with a plasma technique that enhances the bleaching effect without extending the time required.

5. Conclusions

Combined nonthermal plasma and fabricated 15 % HP treatment was analyzed for tooth bleaching effects and changes. This study used a pH neutral 15 % HP gel, applied with plasma to the tooth surface for 30 minutes. An improvement of tooth color was observed at the application of plasma. The color changes were significantly higher in teeth receiving the 30 min bleaching with plasma than that observed in teeth receiving the 10 and 20 min application. Nonthermal plasma source have been used to activate the bleach by promoting the dissociation of HP into radicals. It is proposed that the high amounts of OH generated by plasma activation results in effective tooth bleaching. It describes the motion of our particle under the action of the magnetic field only. There were no significant changes in the microhardness or mineral contents of teeth. Thus, tooth bleaching materials should be selecting according to tooth characteristics. Even though a material has adverse effects, result can be effective without danger if the experimental conditions are carefully followed.

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