

Improving the efficiency of an Er:YAG laser on enamel and dentin

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[au: please provide academic degrees (ie, DDS, DMD) for all authors]

Objective: To evaluate the influence of air pressure, water flow rate, and pulse frequency on the removal speed of enamel and dentin as well as on their surface morphology.

Method and Materials: Twenty-four bovine incisors were horizontally cut in slices. Each sample was mounted on an experimental assembly, allowing precise orientation. Eighteen cavities were prepared, nine in enamel and nine in dentin. Specific parameters for frequency, water flow rate, and air pressure were applied for each experimental group. Three groups were randomly formed according to the air pressure settings. Cavity depth was measured using a digital micrometer gauge, and surface morphology was checked by means of scanning electron microscopy. Data was analyzed with ANOVA and Duncan post hoc test. **Results:** Irradiation at 25 Hz for enamel and 30 Hz for dentin provided the best ablation rates within this study, but efficiency decreased if the frequency was raised further. Greater tissue ablation was found with water flow rate set to low and dropped with higher values. Air pressure was found to have an interaction with the other settings, since ablation rates varied with different air pressure values. **Conclusion:** Fine-tuning of all parameters to get a good ablation rate with minimum surface damage seems to be key in achieving optimal efficiency for cavity preparation with an Er:YAG laser. (*Quintessence Int* 2012;42:xxx-xxx)

Key words: air pressure, efficiency, Er:YAG laser, morphology, water spray

Due to its unique emission wavelength at 2,940 nm (which is extremely well absorbed by water and hydroxyapatite), Er:YAG laser is the preferred type of laser for cavity preparations.¹ However, emission wavelength is only one parameter influencing laser efficiency and its effect on surface morphology of the substrate. Power density, frequency, and pulse length are other important parameters (as they are in the ablation of mineralized tissue) [au: edit ok?].²⁻⁴

Previous studies have demonstrated the influence of pulse frequency on ablation rate in cavity preparations.²⁻⁴ By increasing frequency, more shots are applied and more tooth substance is thus removed during the same time interval, resulting in reduced operation time. On the other hand, increasing energy density seems to have a lesser influence on the laser's efficiency, at least in enamel.^{2,6} [au: cite reference 5]

Because Er:YAG lasers must use water spray for cavity preparation to reduce adverse thermal effects,⁷⁻¹² spray settings represent another issue that may influence the laser's effects. It was shown that external water spray is not only beneficial as a coolant, but also has a significant influence on the ablated volume.¹⁰⁻¹³ The amount of water is also significant, because an excessive amount may decrease the rate of ablation.⁹

Although previous studies demonstrated the influence of water flow rate on ablation rate,^{8,10,11,14} efficiency, and surface morphology, there is no report on the influence of added air pressure to water spray.

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Fig 1 A 3-mm sample fixed on an SEM holder by means of composite resin.

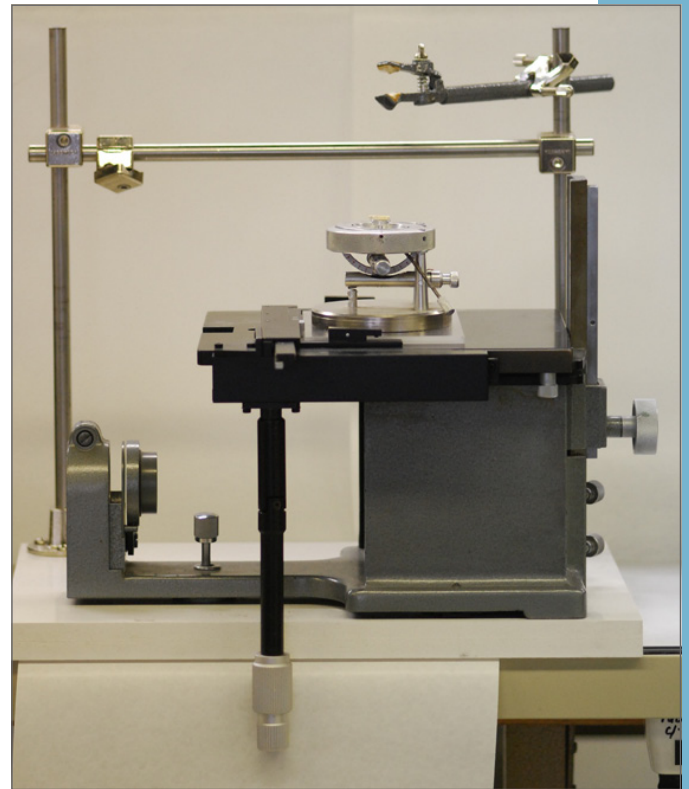


Fig 2 The experimental assembly allowing the precise orientation of the sample in the x, y, and z dimensions by means of micrometric screws.

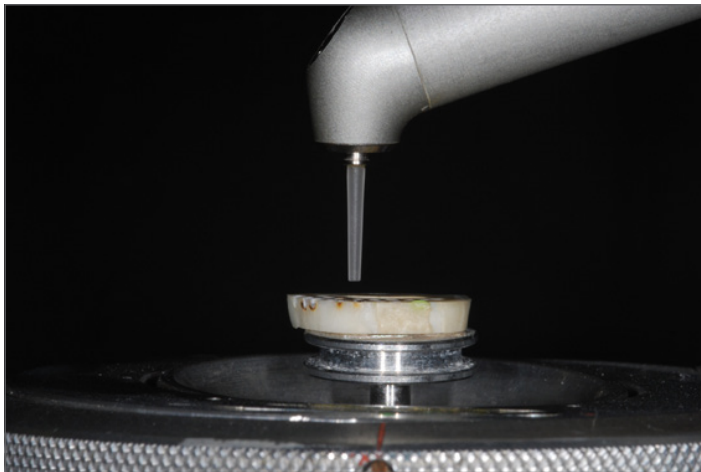


Fig 3 The laser sapphire tip was positioned perpendicularly to the surface of the sample at a 3-mm distance.

Therefore, it was the purpose of this study to evaluate the influence of air pressure and water flow rate, as well as pulse frequency, on the removal speed of enamel and dentin and on their surface morphology. The null hypothesis was that there was

no difference between different spray and frequency settings with respect to dentin and enamel ablation rate, as well as in respect to surface morphology of enamel and dentin.

Substance	Power (mJ)	Air pressure (bar)	Settings		
			Flow setting	Freq (Hz)	No. cavities
Enamel	200	2/3/4	2	10/25/40	3
			5	10/25/40	3
			8	10/25/40	3
Dentin	100	2/3/4	2	10/30/50	3
			5	10/30/50	3
			8	10/30/50	3

METHOD AND MATERIALS

Twenty-four bovine incisors were used in this study. Each tooth was cut horizontally to produce a 3-mm slice (Figs 1 and 2). The slice was fixed on a scanning-electron microscope (SEM) holder by means of composite resin (Tetric, Ivoclar Vivadent) and stored in water up until the experiments began. For cavity preparation, each sample was mounted on a specimen holder and then on an experimental assembly, allowing the precise orientation of the sample in the x,y, and z dimensions by using micrometric screws. The laser sapphire tip was positioned perpendicularly to the surface of the sample at a distance of 3 mm (Fig 3). Eighteen cavities were prepared in each sample, 9 in enamel at the periphery and 9 in dentin in the center of each slice. Each cavity was characterized by four parameters: air pressure, power density, pulse frequency, and water flow rate. The preparation was performed with an Er:YAG laser (LiteTouch, serial no. 002-00096, Syneron Medical) for 5 seconds under continuous water spray cooling with a conical 800 μm sapphire tip. This device allows dentists to vary three settings for cavity excavation: frequency (to increase or reduce the number of shots per second); water flow rate (to better cool the tooth tissue, thus avoiding thermal damage); and air pressure (to allow water spray to reach the substrate between shots). For each experimental group, specific preparation parameters were applied (Table 1). The water flow rate was varied using the laser handpiece settings. Three

	Setting (mL/min)		
	2	5	8
2.0 bar	3.9	8.4	13.4
3.0 bar	5.7	11.0	19.0
4.0 bar	6.8	14.2	22.2

values were chosen to have a low, medium, and high value, which was represented as follows: setting 2 < setting 5 < setting 8. The flow rate in mL/min varied depending on the air pressure settings as reported in Table 2. Since power density influence was not the focus of this study, only one value was chosen for dentin (100 mJ) and one for enamel (200 mJ).

The depth of the cavities was measured using a digital micrometer gauge with a resolution of 70 μm (μS233, serial no. 724556, Sylvac) with a modified, sharpened tip with a diameter of 70 μm.⁹ The tip was carefully put in the deepest spot of each cavity using magnification lenses and by checking different positions of the tip inside the cavity. The micrometer was calibrated prior to each measurement by setting it to zero with the tip next to the edge of each cavity. The mean depth values were submitted to statistical analysis.

In addition, all preparations were optically checked for carbonization by means of magnification lenses and the surface

Table 3 Results of efficiency in enamel with mean and SD for microns/second			
Enamel	10 Hz	25 Hz	40 Hz
2.0 bar			
Setting 2	135.7 ± 4.1 ^a	126.2 ± 63.2 ^a	111.8 ± 28.5 ^b
Setting 5	119.7 ± 21.4 ^b	122.0 ± 40.1 ^a	129.4 ± 49.7 ^a
Setting 8	100.4 ± 20.0 ^c	131.7 ± 24.3 ^a	124.7 ± 29.5 ^a
3.0 bar			
Setting 2	128.8 ± 25.2 ^a	90.2 ± 28.1 ^d	88.2 ± 19.9 ^e
Setting 5	102.3 ± 9.7 ^c	132.9 ± 22.8 ^a	87.7 ± 15.8 ^e
Setting 8	90.2 ± 15.2 ^d	114.6 ± 26.0 ^b	84.3 ± 14.6 ^f
4.0 bar			
Setting 2	114.2 ± 17.7 ^b	153.0 ± 25.6 ^a	105.9 ± 17.8 ^b
Setting 5	116.0 ± 12.9 ^b	129.4 ± 19.1 ^a	89.6 ± 15.0 ^e
Setting 8	131.5 ± 11.9 ^a	130.8 ± 23.3 ^a	87.0 ± 16.5 ^f

SD, standard deviation. The most efficient settings was 4 bar, setting 2, and 25 Hz. Groups with the same letter are not significantly different (ANOVA, Duncan post hoc test; *P* < .05).

Table 4 Results of efficiency in dentin with mean and SD for microns/second.			
Dentin	10 Hz	30 Hz	50 Hz
2.0 bar			
Setting 2	135.7 ± 4.1 ^d	278.4 ± 43.1 ^a	197.4 ± 81.3 ^b
Setting 5	55.0 ± 20.9 ^h	199.1 ± 55.0 ^b	159.9 ± 48.6 ^c
Setting 8	64.3 ± 18.5 ^g	94.5 ± 14.3 ^e	114.6 ± 32.1 ^c
3.0 bar			
Setting 2	79.3 ± 8.4 ^f	275.6 ± 73.7 ^a	223.8 ± 82.5 ^b
Setting 5	62.9 ± 13.5 ^g	117.7 ± 33.8 ^d	130.3 ± 58.8 ^c
Setting 8	54.1 ± 15.7 ⁱ	89.1 ± 20.5 ^e	89.6 ± 35.4 ^e
4.0 bar			
Setting 2	110.8 ± 12.9 ^d	101.0 ± 14.7 ^d	111.8 ± 14.6 ^d
Setting 5	87.5 ± 17.0 ^e	91.4 ± 8.8 ^e	74.7 ± 8.0 ^f
Setting 8	92.1 ± 13.2 ^e	91.8 ± 4.1 ^e	90.3 ± 14.6 ^e

SD, standard deviation. The most efficient settings was 2 bar, setting 2, and 30 Hz. Groups with the same letter are not significantly different (ANOVA, Duncan Post hoc test; *P* < .05).

morphology was observed in the SEM (XL20, Philips) at different magnifications.

A three-way analysis of variance (ANOVA) test was run to evaluate the influence of the variables air pressure, water flow rate, and frequency on the efficacy of different treatments (microns per second) in enamel and dentin groups. The irradiation time was the same for all samples, but we used microns per seconds to better illustrate the cutting efficiency with each setting. A one-way ANOVA was run to determine if there were differences among groups and a Duncan post hoc test to visualize between which

groups these differences were detected. The confidence level was 95%.

RESULTS

The results of efficiency are presented in Table 3 for enamel and Table 4 for dentin.

Frequency

The greatest ablation of dentin and enamel substrate was observed when frequency

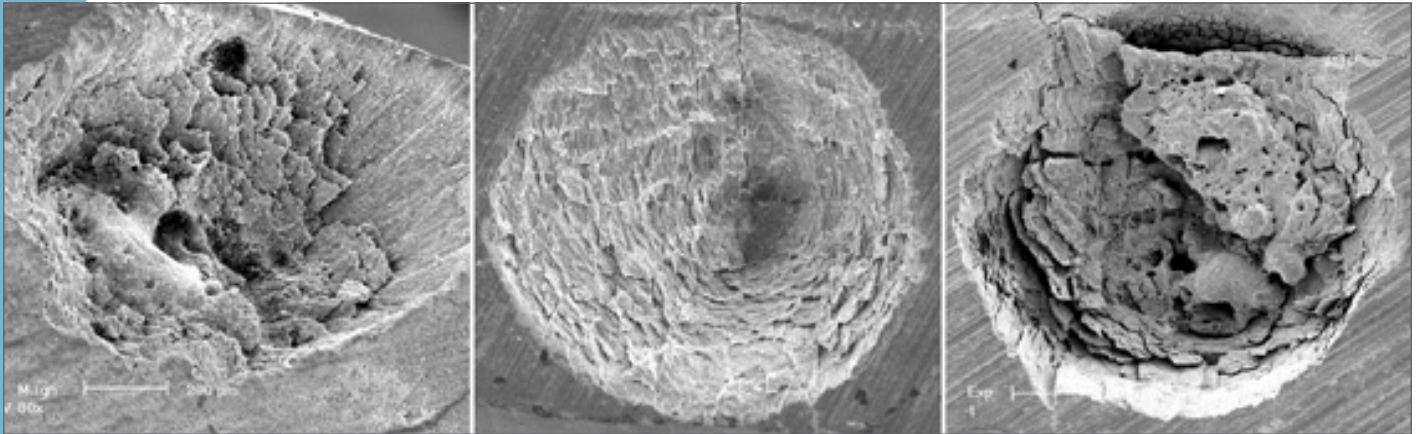


Fig 6 SEM photographs. Surface morphology of enamel cavities with air pressure set to (from left) 2, 3, and 4 bar at 40 Hz and setting 5 [au: renumber as Fig 4?].

was set at 25 Hz for enamel and 30 Hz for dentin. At 40 and 50 Hz, the efficiency decreased as a smaller depth of the cavities was recorded. This drop of efficiency was more important in enamel in both 3- and 4-bar groups, between 25 and 40 Hz. It was found that regardless of any other parameters, laser irradiation at 25 Hz for enamel and 30 Hz for dentin provided the best efficiency within this study.

Water flow

Cavities made with water flow rate set to low (setting 2) were deeper, suggesting a more efficient tissue ablation. Cavity depth decreased while increasing the flow rate from setting 2 to 5 and 8. Although important in the 2- and 3-bar groups, the difference in efficiency between setting 5 and setting 8 was much more subtle in the 4-bar group. Similar effects of water flow rate variation were found both in enamel and dentin.

Air pressure

Air pressure was found to have an interaction with the other parameters varied in this study. The 4-bar group showed the most noticeable differences, especially in dentin with a general decrease in ablation rates at higher frequencies. Generally, the ablation rate would vary with different air pressure while maintaining the same values when changing the other parameters.

When analyzing interactions between all parameters, it was observed that the parameters 4 bar, setting 2, and 25 Hz

showed the greatest ablation for enamel and 2 bar, setting 2, and 30 Hz for dentin.

Statistical analysis

Air pressure and frequency had a significant effect on ablation efficiency in enamel; meanwhile, water flow rate did not have a significant influence on the results ($P = .353$).

The overall analysis of the results showed that an air pressure of either 2 or 4 bar; a water flow rate of 2, 5, or 8; and a frequency of 25 Hz provided the highest results in terms of efficiency. In other words, if a frequency of 25 Hz was applied, two different air pressures and three different water flow rates provided equally good results.

All three variables had a significant effect on treatment efficiency in dentin. The overall analysis of the results showed that an air pressure of 2 bar, a water flow rate of 2, and a frequency of 30 Hz provided with the highest results in terms of efficiency.

Surface morphology

After examination of the surface morphology with both loupes and SEM, the following was found. In enamel, irradiation with air pressure set to 2 bar produced cavities with some fissured and fused areas. Raising the setting to 4 bar increased fissures, irregularities, surface fusion, and ablation depth. Using 3 bar during irradiation promoted a flatter superficial surface topography exempt of fusion [au: figs 4 and 5 not called out, nor were captions provided. Renumber 6 and 7 as 4 and 5?](Fig 6).

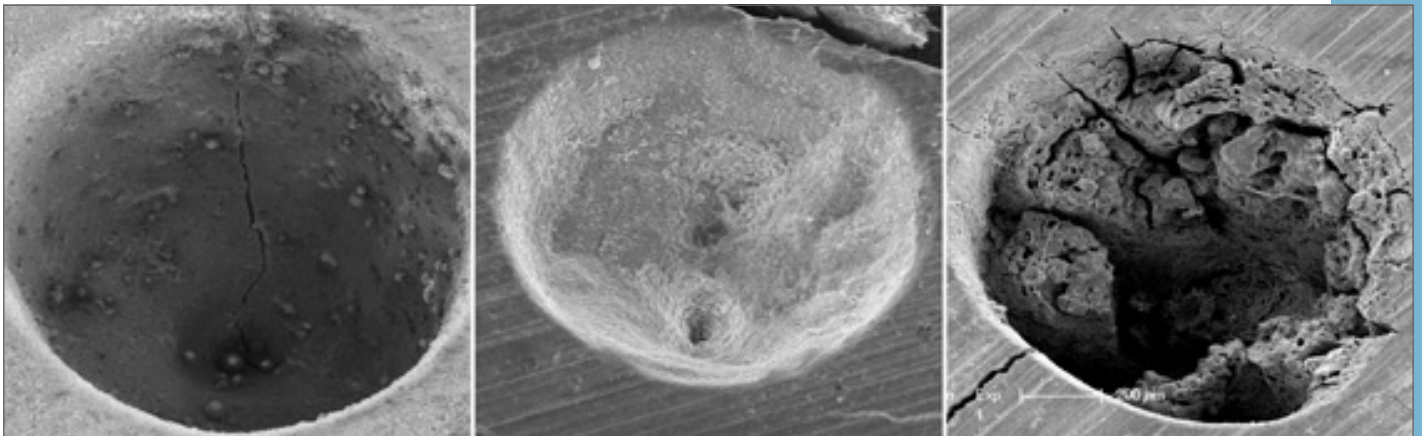


Fig 7 SEM photographs. Surface morphology of dentin with air pressure set to (from left) 2, 3, and 4 bar at 50 Hz and setting 2 [au: renumber as Fig 5?].

The cavities in dentin were checked for burned spots and irregularities, and similar results were observed (Fig 7).

The most efficient settings of 4 bar, setting 2, and 25 Hz in enamel presented a heavily damaged surface with irregularities, evident fissures, and fused areas. For dentin, the best results were obtained with 2 bar, setting 2, and 30 Hz, and the surface morphology presented a few fusion spots and some fissures for these settings. These observations were common for all samples of the same group.

DISCUSSION

To improve efficiency, different parameters of the laser, such as power output and pulse frequency, had to be raised, but by increasing the speed of the preparation, adverse effects on enamel and dentin became more important. Disintegrations, microcracks, loosely bound particles, and burned spots may compromise adhesion and thus increase microleakage of adhesive restorations. This confirms the idea that laser-assisted cavity preparation with efficient parameters must be complemented by finishing with parameters that are less efficient and destructive.¹

This study demonstrated the influence of different parameters on the efficiency for cavity preparation with Er:YAG lasers. The increase of pulse repetition rate had a positive effect on efficiency.⁴ Indeed, a greater amount of tooth substance was removed as the number of microexplosions increased, thus a larger amount of dental substance was removed in less time.⁶ This demonstrated that the increase in efficiency came from the mechanical effect of the microexplosions rather than from the thermal effect obtained when raising energy parameters.^{2,6} However, there seems to be a limit in increasing pulse repetition rate. With higher frequencies (40 and 50 Hz), no further gain of efficiency was found. After examination of the surface morphology of the ablated surface in SEM, many wall irregularities, fusion areas, and fissures were found by increasing the repetition rate. This may be due to the reduced interval between two shots preventing the water spray to wet the surface enough, thus the temperature rises and alterations appear resulting from thermal effects.³ Since the water spray cannot perfectly wet the surface, thermal effects such as melting become predominant over mechanical tissue removal, resulting in a slower tissue ablation.

Previous studies have shown the importance of using a water mist spray during tooth tissue ablation with lasers. With water

spray, the ablation craters have smooth outlines without thermal damage, which is indicative of an entirely mechanical explosive ablation process. In contrast, when used without water, significant alterations of the surface can be observed, such as carbonization.⁹ In this study, it was found that the efficiency decreased when increasing the water flow rate, since the cavities produced with water settings of setting 5 or 8 were shallower than with 2. It was shown in other publications that it is important to have a water layer of sufficient thickness in order to obtain optimal ablation rate, ablation efficiency, and surface morphology of the cavity walls.⁷ The fact that this study obtained better results with a lower water flow rate can be explained as follows: With an excessively thick water film on the dentin surface, the laser energy is absorbed by the water far from the surface and the steam microexplosions do not reach the tissue underneath, thus decreasing the ablation rate.⁹ Under the SEM, the cavities looked more superficial and without surface damage when a high water delivery rate was used (setting 8), confirming the drop of efficiency.

In this study, it was shown that increasing the amount of water does not necessarily increase efficiency, which confirms the findings of Staninec et al.¹¹ It can be hypothesized that the most important factor is not the amount of water but the fine-tuning between frequency and water flow rate. If the interval between shots is long enough, more water will wet the surface and efficiency will be low; if the interval is too short, the available water on the surface will vaporize and the surface will not be rewetted before the next shot. Thus, no further tissue removal occurs and enamel and dentin are instead heated by the laser energy, which induces thermal damage on the cavity surface.¹³ Thus, to increase the efficiency, a high frequency is required but sufficient water is needed between shots.

In this study, air pressure was varied to enhance water delivery between shots. Cavities prepared with the same frequency and water flow rate but different air pressure settings were compared for efficiency. Some showed better results when increasing the pressure, while others showed an

initial increase, but efficiency then dropped when raised further. Others had a decrease of ablation rate when increasing air pressure. This can be explained by the fact that the most important factor for efficiency is the fine-tuning between the different parameters. For each frequency, there might be an optimal water flow rate, and if the frequency rises, water cannot wet the surface between shots. Also, when increasing the water flow rate at a low frequency, too much water may remain on the surface and the explosions may not reach the dental tissue. Since a high frequency is necessary to increase ablation rate, the added air pressure is important so the water is better delivered on the surface between shots. In this way, there is less thermal damage on the surface at higher frequencies and the ablation rate is higher.

After SEM examination, cavities in the 2-bar group showed some thermal damage, which can be explained by the difficulty of wetting the surface between shots at high frequencies since the air pressure was not very strong. The 4-bar group was the one who presented the most damage on the cavity surface, most likely because the pressure was so strong that the water film broke down. Finally, the cavities in the 3-bar group were smooth and presented almost no fused areas or fissures. This means that 3-bar offered the best balance for a water film of sufficient thickness and water delivery between shots.

So far, only frequency and water flow rate have been thoroughly investigated in literature. This study showed the influence of a third parameter (ie, air pressure), which has a direct interaction with the previous ones. This parameter cannot be directly controlled on common Er:YAG lasers on the market, but according to the results of this study, it should be set, at least for the laser evaluated in this study, at 3 bar. Among the tested parameters, 25 Hz, setting 5, and 3 bar for enamel and 30 Hz, setting 2, and 3 bar for dentin improved efficiency without major surface damage.

CONCLUSION

Within the limits of the present study, it can be concluded that increasing the values of all evaluated parameters did not lead to better efficiency. As consequence, the null hypothesis has to be refused.

Fine-tuning of all parameters to get a good ablation rate with minimum surface damage on enamel and dentin seems to be the key in achieving optimal efficiency for cavity preparation with an Er:YAG laser. The optimization of the balance between the three parameters has to be taken into account in clinical works to obtain better efficiency and reduction of operative time.

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