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REVIEW ARTICLE

Water flow on erbium:yttrium–aluminum–garnet laser irradiation: effects on dental tissues

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Abstract Since lasers were introduced in dentistry, there has been considerable advancement in technology. Several wavelengths have been investigated as substitutes for high-speed air turbine. Owing to its high absorbability in water and hydroxyapatite, the erbium:yttrium–aluminum–garnet (Er:YAG) laser has been of great interest among dental practitioners and scientists. In spite of its great potential for hard tissue ablation, Er:YAG laser effectiveness and safety is directly related to an adequate setting of the working patterns. It is assumed that the ablation rate is influenced by certain conditions, such as water content of the target tissue, and laser parameters. It has been shown that Er:YAG irradiation with water coolant attenuates temperature rise and, hence, minimizes the risk of thermally induced pulp injury. It also increases ablation efficiency and enhances adhesion to the lased dental tissue. The aim of this review was to obtain insights into the ablation process and to discuss the effects of water flow on dental tissue ablation using Er:YAG laser.

Keywords Ablation rate · Temperature · Water flow · Erbium:yttrium–aluminum–garnet (Er:YAG) laser · Enamel · Dentin

Introduction

Lasers have been used for dental applications over the past 35 years [1]. Several wavelengths have been investigated as substitutes for high-speed air turbine [2, 3]. Some types of lasers are poorly absorbed by the constituents of dental hard tissue and require a relatively high energy density to vaporize enamel and dentin. The result is poor removal of dental substrate and potential thermal side effects, such as melting, charring or cracking, and even irreversible pulp damage [4–6].

The erbium:yttrium–aluminum–garnet (Er:YAG) laser emits light at a wavelength of 2,940 μm, which coincides with the main absorption peak of water and is well absorbed by the hydroxyl groups in hydroxyapatite. This provides a good interaction with all biologic tissues, including enamel and dentin [7–9]. However, in spite of its great potential for hard tissue ablation, Er:YAG laser effectiveness and safety is directly related to an adequate setting of the working patterns [10]. It is assumed that the ablation rate is influenced by certain conditions, such as water content of target tissue, and laser parameters (e.g., fluence, pulse repetition rate, energy and pulse duration) [10, 11]. Er:YAG irradiation with water coolant attenuates temperature rise [12] and, hence, minimizes the risk of thermally induced pulp injury [13–17]. It also increases ablation efficiency and enhances adhesion to the lased dental tissue [18].

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Our study addressed the influence of water flow on Er:YAG laser ablation of dental hard tissue.

Mechanism of water–laser interaction and its effects on Er:YAG laser irradiation

The mechanism of interaction between water, laser light and hard tissues is not clearly understood and is somewhat controversial [19]. However, the role of water cooling for the effective Er:YAG laser ablation of dental hard tissues is well accepted [20]. Earlier mechanistic studies focused on tissue dehydration [13, 21–23]. However, tissue dehydration due to laser-induced water diffusion was proved unlikely, because only approximately half of the water is actually diffusible [24]. In addition, the diffusion rate is slow (several hours/day). Thermal analysis studies have shown that tissue heating to over 200–300°C would be necessary to produce removal of diffusible water. Temperatures as high as 800°C are required to remove more tightly bound water molecules [25].

It is currently accepted that the rapid subsurface expansion of the interstitially trapped water within the mineral substrate causes a massive volume expansion, which leads to microexplosions and ejection of tissue particles [19]. However, to the best of our knowledge, no published research has substantiated the claim that a single mechanism of action is involved in Er:YAG laser ablation of hard dental tissues [19]. This issue should be further addressed in future studies.

Effect of water flow on laser-ablated tissues

Temperature changes

A localized temperature rise over 100°C is required to achieve tissue vaporization. For dental hard tissue ablation using Er:YAG laser with water coolant, the temperature threshold is close to the critical point of water, between 300°C and 400°C [26]. The laser energy applied to the target tissues, and the heat generated from this energy transference, will also affect, to greater or smaller extent, the adjacent or underlying structures [27]. Thermally induced tissue damage is a function of absolute temperature rise and the duration of this increase [19]. Thus, the optimal laser parameters for dental hard tissue ablation are those that provide effective ablation rates, leaving minimal residual energy for adverse thermal interactions with the enamel/dentin [12] and the pulp tissue [15]. Residual heat deposition on the tooth surface, and pulp temperature rise, are expected to vary markedly with the incident fluence, laser pulse duration, absorption depth in the substrate, water flow rate [13, 14], and the specific mechanism of laser ablation [12].

A large fraction of the energy absorbed from laser pulses is dissipated as internal and kinetic energy of the ablated substrate [12]. After ablation, absorbed laser energy is also lost to radioactive, convective and evaporative cooling of areas from the high-temperature region of the irradiated surface [12]. Moreover, there is re-condensation of the ablated material, and energy is transferred back to the tooth in the form of heat, generating a temperature rise of approximately 15°C [28]. Temperature increase is proportional to the fluence and exposure time, and it is inversely proportional to dental tissue thickness [13, 17, 29, 30].

Temperature increases in dental and pulp tissues can promote undesirable thermal damage [13–17, 31–33]. It has been shown that a temperature rise in the pulp chamber of 5.5°C for 1 min produced irreversible pulpal damage [31]. Another study found that an intrapulpal temperature increase above the threshold of 16°C leads to pulp necrosis [32]. These results are attributed to the fact that heat conduction constitutes the primary mechanism of heat transfer to unexposed tissue structures, whereas the effects of heat convection, e.g., due to the blood flow, are unremarkable, because of the low perfusivity of intra-oral tissues [34]. In addition, the pulp tissue is enclosed within the dentin walls, which reduces heat dissipation and may increase the potential for thermal damage [35]. Several authors [13–17, 33] have reported that Er:YAG laser ablation of dental substrate without water mist promotes a temperature increase above the critical threshold of 5.5°C, therefore being considered a procedure that is potentially harmful to pulp vitality [32]. The excessive increase of intrapulpal temperature and the possible thermal damage to the hard dental tissues have restricted Er:YAG laser ablation of dry teeth.

Water cooling is, therefore, essential to reduce the side effects of temperature rise on biological tissues during clinical use of Er:YAG laser. In a previous study, pulp temperature increases during class V cavity preparation using the Er:YAG laser with water mist did not reach the critical level that could be deleterious to the pulp tissue [36]. Heat produced by Er:YAG ablation is released during water vaporization and tissue microexplosions, leaving relatively little residual heat to be absorbed by the tooth [10, 37]. Uncontrolled energy deposition, though, can produce undesirable thermal damage. Moreover, the water spray cleans the site of irradiation, increases ablation rate efficiency and facilitates the ablation process (Fig. 1) [16]. It has been shown that teeth irradiated with and without water coolant presented peaks of temperature at 3.9°C and 40.86°C, respectively [16]. In addition, an optimal water flow rate can reduce residual heat deposition by almost 50%, without decreasing the ablation rate [20].

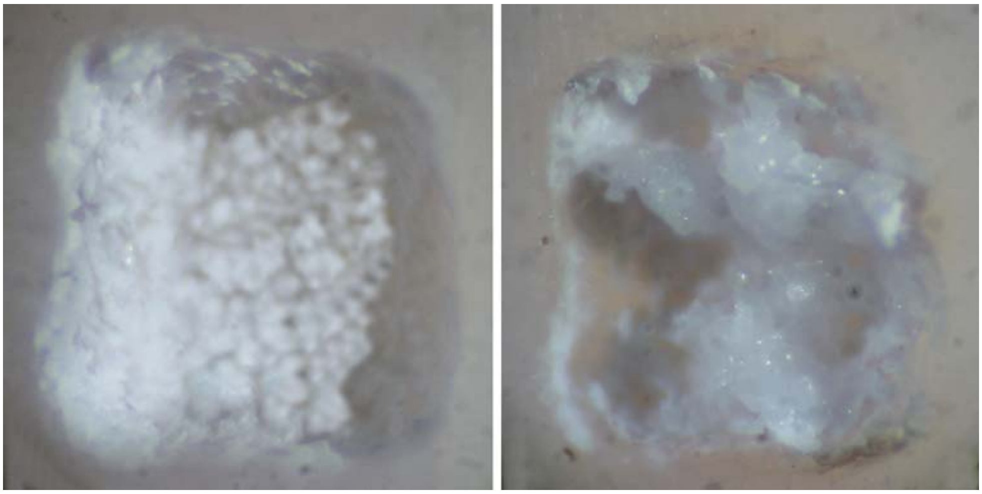

Fig. 1 Enamel irradiated with (*left*) and without (*right*) water flow

Histological, morphological and chemical changes

Histological studies [38, 39] have shown that the use of Er:YAG laser with constant water cooling produces a minimal, reversible and localized pulp response, comparable to that generated by high-speed air turbines. There is no evidence of pulp inflammation or necrosis, periodontal tissues are histologically normal [39, 40], and no changes are observed in pulp tissue vascularization [38]. Besides, when pulp was exposed during laser irradiation with constant water mist, no dentin chips were seen at the exposure site, and a homogeneous dentin bridge was formed at a faster rate by the odontoblastoid cells, which were differentiated from the pulp cells [41].

When Er:YAG laser is employed without water coolant, dark lesions, suggestive of tissue carbonization, large ash flecks, and an irregular ablation pattern are observed [13]. Dry enamel irradiation produces a surface with a molten lava-like appearance, bubble-like voids, large cracks, and irregular fissures [13, 17], which seem to be thermally degenerated (Fig. 2) [42]. Dentinal tubules are not clearly visible and might be sealed by the molten smear layer [13, 17, 42]. On the other hand, enamel surfaces irradiated with water mist has a scaly appearance, while dentin shows a gradual smear layer removal and increasingly visible dentinal tubules [42]. Both enamel and dentin ablated with water mist are smoother than dry-irradiated substrates and present only a slight melting with no thermal damage to the cavity bottom or margins [17, 42, 43]. Enamel and dentin irradiated with and without water floware depicted in Figs. 2, 3, 4 and 5.

Additionally, the use of Er:YAG laser without water mist can induce structural and chemical changes in laser-irradiated tissues [44], such as formation of less desirable non-apatite calcium phosphate phases. Theses regions may be potentially more susceptible to acid dissolution and loosely attached to the underlying unaltered enamel, leading to poor bonding of restorative materials [20]. Although a thick water layer may reduce ablation efficiency, the surface morphology has better quality, consisting of a purer hydroxyapatite with fewer chemical defects. Minor chemical and crystalline changes are also seen in enamel [20]. These changes are likely to be associated with higher bond strength of restorative materials and increased acid resistance [45].

Therefore, Er:YAG laser irradiation of dental hard tissues with constant water coolant avoids undesirable morphological, histological, phases and structural changes in the lased-tissues.

Ablation rate

Laser interaction with tissue depends upon the characteristics of the device and the target tissue. For example, when dentin and enamel are irradiated under the same conditions, dentin is ablated to a greater extent than enamel. This effect appears to be related to dentin's composition: 10% water and 20% organic constituents (by mass), while enamel contains only 1% water and 1% organic material. Dentin's greater water content increases ablation rate in comparison with that of enamel, because ablation is primarily produced by the absorption of laser energy by water [2, 46–49]. Besides, because of its lower water content, peritubular dentin is ablated to a lesser extent than the adjacent collagen-rich intertubular dentin [28, 46, 47, 50, 51].

It has also been shown [2, 52] that, because of its higher permeability and water content, carious dentin is ablated to a greater extent than healthy dentin [53]. A recent study [54] has found that only in dentin did the water content have a significant influence on the ablated volume. Enamel content had no effect on the efficiency of laser ablation. In contrast, the external water supply always had a key influence on ablation efficiency [54]. Colucci et al. [55, 56] have observed that Er:YAG laser ablation of dental

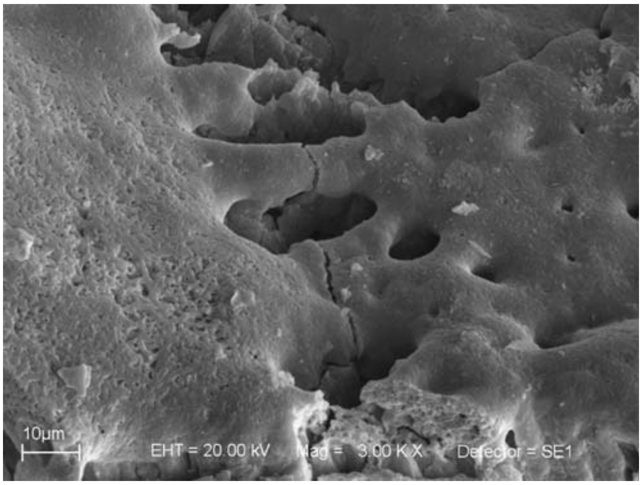

Fig. 2 Enamel irradiated without water flow

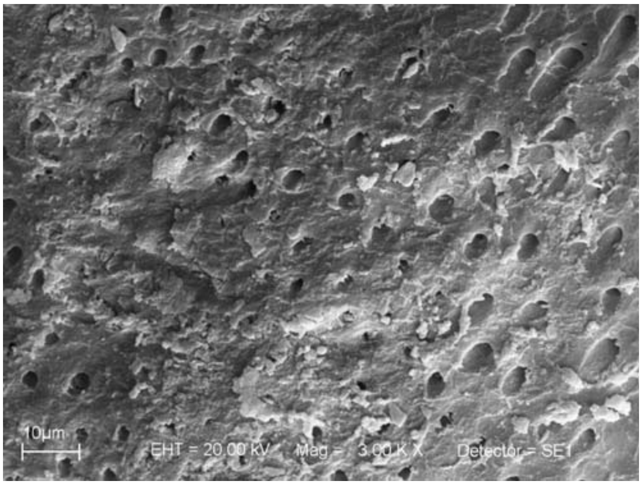

Fig. 4 Dentin irradiated without water flow

tissues with different water flow rates influenced mass loss and strength of bonding of adhesive systems to lased enamel and dentin.

Without water spray, the sequence of laser pulses dries out the tooth surface, resulting in a marked reduction in the efficiency of laser cutting [10, 17]. This occurs because, once the water content has been vaporized, no additional water is available for absorbing laser energy and producing the microexplosions that would lead to the ejection of hard dental tissue in the form of microparticles [57]. When the water flow is not high enough, significant dentin charring occurs, crystallized debris adheres to crater walls, and temperature rises exceed the threshold considered safe to pulp vitality [28].

Irrigation with a fine water spray allows the heat effect of a pulse series to be reduced to that of a single laser pulse when the spray is adjusted to the energy and the pulse repetition rate [58]. Thus, if the pulse repetition rate increases, stronger water flow is needed [17]. However, if the water film is too thick at the ablation site, more energy should be consumed for its removal, thereby decreasing the ablation rate and increasing the number of pulses needed for ablation [26, 31]. The effect of water flow can be optimized by adjusting the amount of water spray in conjunction with other laser parameters [10].

For efficient and safe ablation, Hibst and Keller [31] advocated a water flow rate of 1 ml/min to 2 m/min for a low pulse repetition and energies ranging from 150–250 mJ (0.3–1 W). Using different parameter settings (water flow rate of 1.4 ml/min, 4 Hz and 140 mJ), Armengol et al. [14] found efficient ablation without melting or cracking, as reported elsewhere [31]. Kim et al. [10] found that the optimal water flow rate for enamel ablation with 400 mJ energy was 6.75 ml/min. However, dentin was efficiently ablated with a water flow rate of 1.69 ml/min, using the same energy. In addition, the influence of water flow rate decreased as laser energy decreased. The lower energy, 250 mJ per pulse, resulted in similar water flow requirements by both enamel and dentin, which showed that the most effective ablation occurred at the lowest water flow rate of

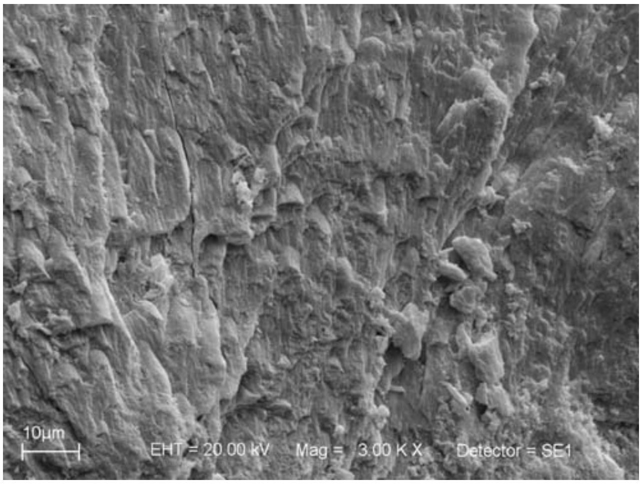

Fig. 3 Enamel irradiated with water flow

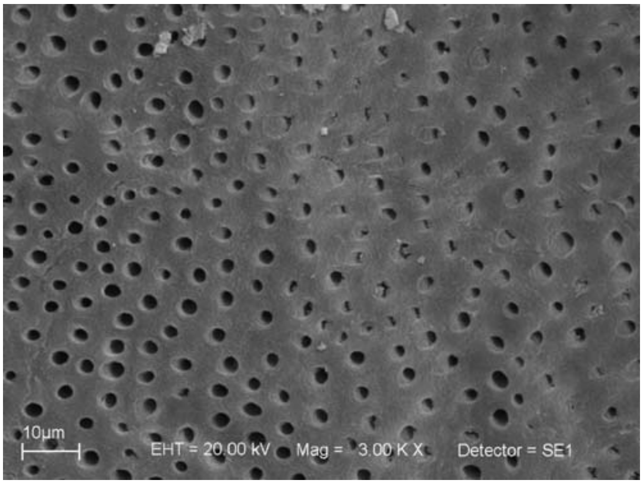

Fig. 5 Dentin irradiated with water flow

1.69 ml/min. These results show that the thickness of the water film formed on the tooth surface has a greater influence on ablation rate at lower Er:YAG laser energies [10].

In summary, an adequate water flow rate during laser irradiation not only enables more efficient enamel/dentin ablation, but also offers thermal protection to the pulp and improves the adhesion of restorative materials to laser-irradiated substrates.

Er:YAG laser X high-speed handpiece

Er:YAG laser has been used in dentistry for several years, with advantages and disadvantages compared to bur preparation of enamel and dentin. The major limitations for the spread of Er:YAG laser technology in dental practice is the high equipment cost, limited access [51] and need for longer chairtime.

Removal of both healthy and carious dental tissue with Er:YAG laser is slower than with conventional high-speed rotary instruments, especially when cavity preparation involves enamel and deep and large carious lesions [51]. On the other hand, the laser systems offer several advantages over the conventional high-speed handpieces. Bur-prepared teeth are unavoidably associated with the production of a metallic sound and bone-conducted vibration that might cause patient discomfort and anxiety [51]. Patients have been shown to have a greater tolerance to laser treatment and usually refer minimal or no pain due to the lack of noise and vibration [58, 59]. Bactericidal and anti-infective effects have also been verified with Er:YAG laser irradiation [60].

Further research should yet improve Er:YAG laser ablation of dental hard tissues and clarify its effects on the adhesion of restorative materials and intrapulpal temperature rise. Laser technology has a promising future in dental practice, provided that laser devices become available at a reasonable cost and have their effectiveness improved.

Insights into previous studies and future perspectives

The importance of water flow to safe and efficient ablation of the dental tissues with Er:YAG laser has been exten-

Table 1 Summary of the most frequently used laser parameter settings

Reference	Subject	Dental substrate	Laser parameters					
			Energy/energy density/ power	Frequency (HZ)	Beam diameter (mm)	Pulse duration	Water flow rate	Water delivery
Cavalcanti et al. 2003 [16]	Temperature	Bovine incisors	350 mJ 3.5 W	10 Hz	–	250 µs	4.5 ml/min	–
Atrill et al. 2004 [15]	Temperature	Human premolar	230 mJ	2, 4 or 8 Hz	–	200–250 µs	3–5 ml/min	Syringe/ fine needle
Fried et al. 2001 [12]	Temperature	Unerupted third molars/bovine incisors	100 J/cm^2	–	–	150 µs	0, 5 and 15 µl	Automatic pipette
Park et al. 2007 [61]	Temperature	Human molars	300 mJ	20 Hz	–	–	1.6 ml/min	Spray
Hossain et al. 1999 [17]	Ablation depths and morphological changes	Human incisors and molars	100, 200, 300 and 400 mJ	2 Hz	0.63 mm	250 µs	0 and 1.0 ml/min	–
Staninec et al. 2003 [18]	Bond strength	Bovine incisors	10 J/cm^2 to 100 J/cm^2	–	–	–	0 to 2 ml/min	Syringe pump
Visuri et al. 1996 [28]	Ablation rate and temperature	Human molars and premolars	110 J/cm^2	2 Hz	0.7 mm	230 µs	0 to 11 ml/min	–
Meister et al. 2006 [54]	Ablation rate	Bovine incisors	1 00 to 150 mJ, 56 J/cm^2, 1 W, 0.5 W	5 Hz to dentin and 10 Hz to enamel	474 µm	125–250 µs	0, 0.8, 3.0 ml/s	Spray air/ water
Burkes et al. 1992 [13]	Ablation rate	Human molars and premolars	56 mJ, 60 mJ, 95 mJ	–	–	250 µs	“fine water mist”	Spray
Kim et al. 2003 [10]	Ablation rate	Human molars	250 mJ and 400 mJ	5, 10 and 15 Hz	–	100 µs	1.69, 6.75 and 13.5 ml/min	–

sively investigated [10, 12–18, 20, 55, 56, 61]. However, a review of the literature raises some important issues, especially those regarding the laser parameters employed. The most frequently used laser parameter settings are summarized in Table 1. A large number of studies, however, omit important information, such as, energy density, power, laser beam diameter and water delivery mode, which jeopardizes inter-study comparisons.

Laser beam diameter and pulse duration are not commonly mentioned in laser studies [10, 12–18]. In addition, several authors erroneously refer to the spot size given by the laser device's manufacturer as being the beam diameter. Uniform dosimetry is a prerequisite for reproducible laser applications in research and practice. The light–tissue interaction is directly dependent on energy distribution within the laser beam [62]. This means that accurate knowledge of the spatial beam profile and pulse duration is essential [62] to improve future comparison among studies. It has been shown that the intrapulpal temperature rise that normally occurs during dental ablation with a laser pulse duration around 100 µs could be mitigated if a 10 µs pulse duration was used. In this case, a less strong water flow would be needed [63].

Different substrates have been used in laser studies. Although bovine and human teeth have been shown to present qualitative similarity in caries progression [64] and bonding tests [65, 66], laser–bovine substrate interaction has yet to be demonstrated. Thus, it cannot be predicted whether the bovine substrate could have had any specific influence on study outcomes. Regarding the studies with human teeth, different types of teeth (premolars, molars, incisors) have been used, which may also have influenced the results because of the characteristics of each tooth group. Thus, future research should explore the interaction between the Er:YAG laser and different substrates, in order to obtain an adequate alternative for the laser studies.

Other issues that have not yet been addressed are the influence of the temperature of the water used for cooling of dental hard tissues during Er:YAG laser irradiation and also the best method of water flow delivery. Moistening the tissue, for example, might be advantageous over using a water stream. Future research should investigate the influence of these issues on ablation rate, morphological changes, and pulp temperature rise. Furthermore, it is important to consider that different types of lasers have been used for cutting dental hard tissues besides the Er:YAG laser. Given that the interactions of dental tissues with light energy are influenced by both laser and target tissue characteristics, the results obtained with water-mediated cooling for other lasers may either support or confront the currently known evidence for the Er:YAG laser. There is a consensus on the fact that Er:YAG laser irradiation with water cooling is safe and efficient for the removal of enamel and dentin. However, water cooling may have a different impact on treatment at other wavelengths. A previous study [67] has shown that Nd:YAG laser irradiation of dentin with water mist had lesser thermal effects, but the generated temperature rise, despite the coolant, may still cause pulp damage. When carbon dioxide (CO_2) laser was employed on enamel, both water- and air-cooling methods were effective in preventing thermally induced pulp damage [68]. The impact of the laser beam on the target tissue leads to the transformation of radiant energy into heat by absorption. Each laser wavelength has a different absorption rate and interaction with the biological tissues. Thus, the use of water-mediated cooling has different results according to the type of laser. In addition, the literature lacks aspects related to the influence of water flow on irradiation performed with lasers other than the Er:YAG laser.

In summary, even though the use of water flow in Er:YAG laser irradiation is well established, further studies with more complete documentation of parameter settings are needed in this field in order to improve future inter-study comparisons and clarify the issues addressed in this paper.

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