Abstract: A number of concepts and devices have been proposed for caries removal. Among these, the Er:YAG laser is a potential alternative to conventional mechanical treatment. This study compared the effectiveness of the Er:YAG laser with that of low-speed rotary instruments for removal of carious tissue in 26 extracted human molars and premolars with severe decay (i.e., large occlusal or proximal decay but no pulpal contact). The teeth were divided into three groups of eight teeth, and two teeth were used as controls. After sectioning all the teeth through the center of the carious lesion before excavation, each group was randomly assigned to three groups—Er:YAG laser versus tungsten bur, Er:YAG laser versus polymer bur, and polymer bur versus tungsten bur—to evaluate the efficacy of the three techniques. The time required for carious treatment of each half was recorded, and samples were then histologically examined. Mean duration of caries removal did not significantly differ in relation to the technique used. Histological analysis of tooth halves treated with the Er:YAG laser revealed a regular 5-µm-thick stained layer that appeared to be denatured collagen. A smear layer was often detectable in halves treated with carbide burs. A superficial disorganized layer, which was found to be affected dentin, was observed in halves treated with polymer burs. The present findings indicate that the three techniques were clinically and histologically effective in removing the infected dentin layer. (J Oral Sci 58, 583-589, 2016)

Keywords: caries removal; Er:YAG laser; carbide bur; polymer bur.

Introduction
Over the last few years the treatment of dental caries has changed, and carious lesions are now frequently treated with less invasive methods that favor tissue conservation. When dentin caries removal is indicated, softened carious tissues are ablated to eliminate the bulk of the infected tissue, to prevent re-development of the lesion, protect pulp vitality, and prepare a clean cavity for restoration. To attain these objectives, numerous techniques have been proposed. Banerjee et al. (1) proposed the following requirements for dentin removal techniques: comfort and ease in the clinical environment, ability to discriminate and remove only diseased tissues, painless and silent treatment requiring only minimal pressure without vibration or heat during periods of operation, and, finally, affordability and ease of maintenance.

Dentin caries removal is generally accomplished using mechanical procedures with instruments such as rotary carbide burs and/or a hand excavator, which are often preferred by practitioners. Usually, tactile and optical criteria are used to evaluate the cleanliness of the prepared cavity; however, these clinical criteria are totally subjective, as they depend on operator judgment and experience (2). Dyes are often used to stain carious dentin but are not considered absolutely reliable (3). To avoid unnecessary treatment, a diagnostic aid should yield very few false positives. However, dyes do not stain bacteria—they stain the organic matrix of less mineralized dentin. Such dyes neither stain bacteria nor delineate the bacterial front but rather stain collagen associated with the less mineralized organic matrix. Dye staining and bacterial penetration are independent phenomena; thus, the usefulness of these dyes for diagnostic purposes is limited. Dye-stainable status may not be a good indi-
cator of bacteria presence or absence in dentin and lacks specificity for accurate detection of carious dentin (4).

Recently, new techniques have been developed, such as lasers, chemo-mechanical removal (Carisolv System) (5), air abrasion, and sono-abrasion. Previous studies reported that they are more or less successful than mechanical procedures (carbide bur); however, even though these techniques are noninvasive, they do not fulfill all treatment requirements.

A new polymer bur developed by Boston in 2003 (6), the Smartprep, has interesting characteristics. According to the manufacturer, this polymer is harder than infected dentin but softer than affected and sound dentin, particularly sclerotic discolored dentin, thus allowing precise caries removal.

Since the discovery of the ruby laser by Maiman in 1960 and the first application to dental tissue by Goldman in 1964, other lasers using argon, carbon dioxide, and neodymium-doped:yttrium-aluminium-garnet (Nd:YAG) have been developed and tested by researchers but cannot cut hard dental tissues. The erbium-doped:yttrium-aluminium-garnet laser (Er:YAG) emits at a wavelength of 2.94 µm in the mid-infrared region and has great potential for dentin removal because of its high absorbability in water and hydroxyapatite (7). It belongs to the erbium laser family, along with the Er,Cr:YSGG, which emits at 2.78 µm and has its best absorption in hydroxyapatite.

Dentin surfaces treated by lasers appear clean, without a smear layer, and have open and clear tubules (8). Thermal elevation in the pulp, recorded during Er:YAG laser irradiation, is lower than that recorded when a turbine and micromotor are used under the same air/water spray conditions (9-10). The 2940 nm wavelength also has an antimicrobial decontamination effect on treated tissue, thus destroying aerobic and anaerobic bacteria (11). The most interesting aspects of this new technology are related to the goals of modern conservative dentistry, i.e., minimally invasive treatments and adhesive dentistry. Er:YAG lasers can reach spot dimensions smaller than 1 mm, which enables selective ablation of affected dentin while preserving surrounding sound tissue, thereby producing highly efficient restorations (12). Several in vitro studies reported that preparation of enamel and dentin by Er:YAG laser, followed by orthophosphoric acid-etching, increased effectiveness by reducing microleakage and increasing bond strength (13). All these characteristics result in very high patient comfort (14).

An in vitro study in 1998 (15) found that a new Er:YAG laser with a contact probe system effectively ablated carious dentin and resulted in minimal thermal damage to surrounding intact dentin. In addition, removal of infected and softened carious dentin was similar to that of carbide bur treatment, but with longer treatment time.

Because of the present interest in noninvasive dentistry, this in vitro study evaluated and compared the treatment effectiveness of three dentin excavation methods—the carbide bur, polymer bur, and Er:YAG laser—in extracted carious human teeth.

**Materials and Methods**

We studied 26 extracted human teeth with large occlusal or proximal decay, but no pulpal contact. The mean distance from pulp tissue was 1 mm (as confirmed by radiography). These samples were collected in accordance with a protocol that satisfied the ethical standards of the “Centre Hospitalier Universitaire de Nice”: the teeth were extracted because of the effects of diagnosed periodontal lesions and were obtained from patients who had consented to their use for research purposes. The teeth were stored at 4°C in individual plastic containers filled with physiological serum for a maximum of 7 days before carious treatment.

**Dentin removal methods**

Round tungsten carbide burs (#H1S 204012 and 014, Komet, Besigheim, Germany) mounted on a low-speed contra-angle (2,000 rpm) handpiece were used to remove carious dentin in a conventional concentric movement from the periphery to the center of the lesion, until contact with sound dentin. The clinical criteria used to assess the quality of this removal technique were dentin color and hardness (probe-checking). A new bur was used for each sample.

Round polymer burs (Smartprep, now marketed as Smartbur; SS White Inc., Lakewood, NJ, USA), reference #40021 RA-4 (ISO 014) and #40020-1 RA-2 (ISO 012), mounted on a very-low-speed contra-angle (500-800 rpm) handpiece were used for soft carious tissue removal according to the manufacturer’s recommendations. A conventional concentric movement from the center to the periphery of the lesion, with slight pressure but without contact with enamel, sound dentin, or old restoration material, was used in order to avoid rapid bur wear. Because the hardness of the polymer bur is less than that of enamel and sound dentin, excavation was stopped when the instrument became macroscopically abraded or blunted and was no longer able to remove tissue. A new polymer bur was used for each sample.

An Er:YAG laser (Fidelis II, Fotona, Ljubljana, Slovenia) was used under the following conditions: wavelength, 2.94 µm; sapphire-tip R1014 handpiece...
(diameter 0.8 mm) in quasi-contact mode; frequency, 10 Hz; pulse duration (SSP mode), 50 µs; power meter (Ophir Optronics Ltd., Jerusalem, Israel) measured output energy, 375 mJ; theoretical fluence, 69.6 J/cm². Power meter evaluation was performed at the start of the experimental procedure because of the stability of this wavelength.

Caries removal took place under air-water spray (7 mL/min, ratio 25-20), and laser irradiation was regularly stopped so that a probe could be used to determine dentin condition and stop the irradiation once healthy tissue was reached.

Experimental procedures
The protocol described by Aoki et al. (7) and modified by Celiberti et al. (3) was used in this study. Before carious tissue excavation, each carious lesion was divided by a groove into two parts of approximately equal size, using a high-speed diamond bur under air-water spray (Fig. 1). Four groups were randomly formed, as follows. A control group of two untreated carious teeth was assigned to histological analysis. The remaining 24 teeth were divided into three groups of eight teeth each. In group A, half of the carious lesion of each tooth was treated with the Er:YAG laser, and the other half was treated with a polymer bur. In group B, half of the carious lesion of each tooth was treated with the Er:YAG laser, and the other half was treated with the carbide bur. In group C, half of the carious lesion of each tooth was treated with the carbide bur, and the other half was treated with the polymer bur.

For polymer bur excavation, a training session was carried out to familiarize the operator with this new bur. The times required for each method and each treated half-lesion were recorded, without including the time required for inspection of residual tissues. After dentin removal was complete, each half-lesion was separated from the other, by fracture, to avoid undesirable debris contamination. Samples were then stored for 48 h in individual containers filled with 4% buffered formaldehyde solution, for fixation. After this, samples were prepared for histological analysis. After decalcification, dehydration, and embedding in paraffin blocks, serial cross-sections (thickness 2 µm) were cut parallel to dentinal tubules. The sections were mounted on slides and stained with Hematoxylin Eosin Saffron (HES) for topographic examination, using an automatic staining device (Varistain 24-4, Thermo Shandon Ltd, Runcorn, UK). All sections were examined under a light microscope (Olympus, Tokyo, Japan; original magnification ×150–1,500).

The efficiency of the different excavation methods was examined by using the image analysis program Noesis 5 (Noesis Solutions, Leuven, Belgium). The presence of infected, affected, or sound dentin (yes/no) and the presence of microorganisms on the surface (yes/no) and in dentinal tubules (yes/no) were investigated.

Data analysis
The time required for excavation was compared using nonparametric tests (Kruskal-Wallis test and Mann-Whitney U test). The McNemar test was used for qualitative statistical analysis of the efficiency of the excavation methods.

Results
Time required
The average time required was 36 ± 16 s for the tungsten carbide bur group, 37 ± 20 s for the polymer bur group, and 35 ± 15 s for the Er:YAG laser group (Fig. 2). No statistically significant difference was observed within the three groups (P = 0.9883).

Qualitative histological analysis (Table 1)
The McNemar test revealed that in group A (Fig. 3) there was no significant difference between the Er:YAG laser
and polymer bur in relation to remaining infected dentin ($P = 1.000$); both techniques removed it satisfactorily. However, there was a significant difference ($P = 0.008$) in remaining affected dentin. The highest percentage of sound dentin was observed when the Er:YAG laser was used ($P = 0.008$). There was no significant difference in bacteria presence on the surface or in dentinal tubules ($P = 1.000$).

All samples in group B were free of infected dentin (Fig. 4). Thus, the McNemar test could not be used. There was no significant difference between the laser and carbide bur in relation to affected dentin ($P = 0.500$); both techniques removed it. These techniques cleaned the cavity surface equally well ($P = 0.500$), but a smear layer was observed when the carbide bur was used. Dentin surfaces and dentinal tubules were bacteria-free in all samples (McNemar test not possible).

In group C (Fig. 5) there was no significant difference between polymer and carbide burs in relation to the presence of infected, affected, or sound dentin ($P = 0.500$, $P = 0.625$, $P = 1.000$, respectively). There was no significant difference in bacteria presence on the surface or in dentinal tubules ($P = 1.000$).

**Discussion**

Under the present experimental conditions, adapted from Aoki et al. (15) and Celiberti et al. (3), it was impossible to treat carious lesions of the same size with the same volumes of infected, affected, and sound dentin. In the three groups of eight teeth, each specimen was divided into two parts; thus, 16 samples were treated with each technique. This protocol maximized similarity and harmonization. Moreover, we decided to divide each carious lesion into halves before treatment, so that any debris contamination would be the same for all examined samples. Two different operators performed the decay removal: one used lasers, the other used carbide and polymer burs. Allen et al. noted that polymer burs were unable to remove scar and sound dentin; the present results confirm this, except for three samples in group C. Previous studies reported that Er:YAG lasers and carbide

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**Table 1** Qualitative analysis of treatment effects (McNemar test)

| Group   | Infected dentin | Affected dentin | Sound dentin | Bacteria on subsurface | Bacteria in dentinal tubules |
|---------|----------------|-----------------|--------------|------------------------|-----------------------------|
| A       | 1.000          | 0.008           | 0.008        | 0.500                  | 1.000                       |
| B       | Unfeasible     | 0.500           | 0.500        | 1.000                  | Unfeasible                  |
| C       | 0.500          | 0.625           | 1.000        | 1.000                  | 1.000                       |

All data are $P$ values.
burs can remove these hard tissues in non-selective mode (16). The sapphire tip of the Er:YAG laser can be used as a probe to check the hardness of the superficial layer, after irradiation has been interrupted.

The 2.94-µm wavelength of the Er:YAG laser is strongly absorbed by water and minerals and thus removes dentin by means of explosive water-mediated ablation (thermomechanical ablation). Light is absorbed by water molecules, heats a small volume rapidly, and water vaporization creates a strong subsurface pressure leading to explosive removal of targeted tissue. Dentin ablation under the present experimental conditions (contact mode, frequency 10 Hz, pulse duration 50 µs (SSP mode), power meter-measured output energy 375 mJ, theoretical fluence 69.6 J/cm², air-water spraying 7 mL/min, ratio 25-20) did not cause thermal damage to pulp (17-18).

Histological observation revealed a strongly stained layer in all Er:YAG laser-irradiated samples. This 5-µm zone was identified as a layer of slightly denatured collagen, and its microhardness was slightly lower than that of bur-prepared dentinal surfaces. Aoki et al. (15) hypothesized that this layer is caused by a thermomechanical effect resulting in microstructural degeneration of lased dentin. The same lased dentinal surfaces, under scanning electron microscopic observation, exhibited irregularities likely attributable to the fact that the water content of intertubular dentin is higher than that of peritubular dentin. Moreover, dentinal tubules are always open and no smear layer is present (19-21). The present histological results confirm the absence of a smear layer in lased samples.

Oikawa et al. (22) found the polymer bur removal technique to be insufficient. Their conclusion was based on an analysis of dentinal tissue remnants with a caries indicator (red stain), the Caries Check and DIAGNOdent systems. Evaluating the so-called self-limiting concept in dentinal caries removal, Silva et al. (23) reported areas of incompletely removed denatured caries-infected dentin in polymer bur specimens but not in carbide bur specimens. Moreover, they found that the dentin remaining after polymer bur removal was hard, discolored, and/or pigmented.

The same authors reported that the bond strength of a composite restoration to surfaces prepared with a polymer bur was significantly lower than that for surfaces prepared with a carbide bur when different bonding agents were used (23). They concluded that the composition/hardness of the polymer bur should be modified to ensure complete removal of infected tissue. Moreover, in recent clinical studies patients experienced slightly more pain, pressure, vibration, and anxiety—but no excess heat, cold, or fear—during treatment with a polymer bur. However, some studies (24-26) concluded that polymer burs and carbide burs were similarly effective for caries removal. Our histological observations revealed the systematic presence of a lightly stained layer resembling affected dentin (disorganized structure with a thickness of 5 µm). After using polymer burs, Lopes et al. (27) reported a structurally disorganized dentinal surface without infected dentin. Their results suggest that collagen fibers are not totally surrounded by hydroxyapatite crystals, which indicates the presence of demineralized areas, in contrast to the sound dentin found after carbide bur removal. This substrate is more easily damaged by acids, when bonding systems are used. Peters et al. (28) recommended the use of polymer burs as an ultraconservative technique for dentin removal that results in a consistent and relative layer of affected dentin. Yoshiyama et al. (29) concluded that this layer is affected dentin. Sichike et al. (30), however, considered this layer to be sound dentin, in their comparison of Knoop microhardness for the polymer bur and carbide bur removal techniques.

Traditional mechanical removal technique using a carbide bur routinely over-prepares the cavity. Moreover, the carbide bur is difficult to control because of its high efficiency in cutting dentin. Thus, infected, affected, and sound dentin is removed with little tactile feedback (23). Previous studies (31-33) indicate that carbide burs produce an obvious smear layer. However, our histological observations revealed a few samples without a smear layer or with a partially removed smear layer. We believe that the layer had been eliminated in part by the acid decalcification technique used for histological preparation.

From a clinical perspective, caries removal should eliminate infected dentin, which is a poor substrate for adhesion, and preserve affected dentin that is only partially demineralized. Affected dentin contains intact non-denatured collagen and is amenable to remineralization. For the moment, the polymer bur may be inadequate for complete removal of infected tissue, while both of the other bur types are indiscriminate in removing hard tissues. The main advantage of Er:YAG laser treatment is the bactericidal effect in the deep dentin layers. Water dissociation generates hydroxyl radicals, which eliminate microorganisms, even when low fluencies are used to discriminate between removal of affected dentin versus infected dentin (34). This characteristic of the Er:YAG laser could help prevent further carious relapse.

The present results indicate that all three techniques
were clinically and histologically effective in removing the infected dentin layer. Large, multicenter, randomized controlled trials should further examine the efficacy of laser treatment over conventional and/or polymer bur treatment of carious lesions.

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Conflicts of interest
None declared.

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