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Comparison of Methods for Measuring the Ablation Efficacy of Erbium Dental Lasers

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ABSTRACT

The ablation efficacy of hard dental tissue, in terms of ablated volume per laser energy, is one of the most commonly used parameters for comparing and optimizing Erbium dental lasers. A number of techniques have been applied to measure the ablation of crater volumes. Two of the most common methods use a focusing optical microscope and a laser triangulation technique. The laser triangulation technique measures the actual crater shapes while the microscope technique is based on an assumption that the crater is cylindrically shaped. This may lead to a discrepancy between published reports when different experimental methods are used. In this paper we report on a comparison of measured volumes as obtained with the microscope and the triangulation technique. An approximate relationship between the two volumes is obtained which allows for a comparison of published data regardless of the measurement technique used. Our measurements also show that the shapes of shallow craters are approximately conical, while the shapes of deeper craters are between a conical and a cylindrical shape.

Key words: Er:YAG, laser dentistry, ablation efficacy, enamel, hard dental tissue.

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I. INTRODUCTION

Pulsed mid-infrared Erbium lasers are by now an accepted minimally invasive tool for treating hard dental tissues [1-4].

When comparing different Erbium laser wavelengths and pulse modes, much of the research and development work has been focused on optimizing laser ablation efficacy (AE), defined as ablated crater volume (V, in mm^3) per delivered laser energy (E, in J), and calculated from AE = V/E (in mm^3/J) [5-7].

The procedure to measure the ablation efficacy usually involves the irradiation of a tooth with a number of consecutive laser pulses to produce a measurable crater, followed by the measurement of the crater depth or volume. In early experiments [8], the laser-ablated craters were examined under an optical microscope and the crater depth was determined by means of an ocular micrometer. Majaron et al. [9] used optical stereo-microscopy to determine the crater depths. Sarafetinides et al. [10] sectioned the teeth into slices of equal thickness and measured the time needed to perforate a slice at a constant pulse repetition rate. Later, Forrester et al. [11] used scanning electron microscopy (SEM) to determine the volume of laser-ablated craters. Rode et al. [12] constructed a three-dimensional (3D) model of a laser-ablated crater using extended depth-of-field digital imaging. Ohmi et al. [13] monitored laser ablation in situ using an optical coherence tomography (OCT) set-up. And Mercer et al. [14] have employed X-ray microtomography (XMT) to determine the 3D shapes of laser-ablated craters at micrometer resolution.

Mehl et al. [15] have employed a 3D laser scanner to determine the volume ablation rate. Impressions of teeth were taken before and after the laser ablation and measured by a laser triangulation scanner. Later, a faster optical triangulation method was developed which allows rapid and accurate in-vitro measurements of the three-dimensional (3D) shape of laser ablated craters in hard dental tissues and the determination of crater volume, V_{tri} [16-19]. The triangulation technique provides a relatively accurate measurement of the actual crater volume ($V \approx V_{tri}$). On the other hand, when using the focusing optical microscope technique, which still remains a very common method for determining ablation efficacy [5-6], the volume of the ablated crater is estimated from $V_{mic} = (\pi d^2/4) \times L$, where it is assumed that the crater is a cylindrically shaped hole having a constant diameter d over the depth L of the crater. Since in reality the diameter of the hole gets smaller towards the bottom of the ablated cavity, the actual ablated volume as would be measured using the triangulation technique is smaller than V_{mic}. Ablation efficacies as obtained with the optical microscope technique are therefore higher than as measured using the triangulation method. This may not represent a significant problem when comparing different laser modalities using the same method. However, this difference must be taken into account when comparing data from different reports using different measurement techniques. For this reason, in order to avoid confusion, some authors define the ablation efficacy as obtained from optical microscope measurements as ablation drilling efficacy (DF, in mm^3/J), defined as depth per laser fluence (F, in J/mm^2) [6].

In this paper, we measured ablation volumes using both techniques: the optical focusing microscope and the laser triangulation method, and by comparing both volumes obtained an approximate relationship between V_{tri} and V_{mic} . We show that this relationship allows for comparison with published data regardless of the measurement technique used.

II. MATERIALS AND METHODS

The Erbium lasers used were an Er:YAG (λ = 2.94 μm) LightWalker system (manufactured by Fotona) and an Er,Cr:YSGG (λ = 2.78 μm) Waterlase iPlus (manufactured by Biolase). The lasers were fitted with non-contact handpieces (a Fotona H02 handpiece and a Biolase Turbo handpiece equipped with an MX 11 tip).

Extracted premolar and molar teeth were selected and, immediately following extraction, stored in a physiological saline solution. The teeth were randomly chosen for the ablation experiments. Before each ablation experiment, the tooth was positioned with its surface perpendicular to the laser beam and at the focal distance of the laser beam. The approximate beam diameters at the focus were 0.9 mm (H02) and 0.7 mm (MX11).

Water spray cooling as provided by the laser systems was used in the experiments. The laser systems' spray settings resulted in measured water flows of 16 ml/min and 32 ml/min for Er:YAG, and 21 ml/min for Er,Cr:YSGG. Water flow rate was determined by measuring the time and water volume collected in an external container during that time.

Ablation cavities were made in enamel with a different number (N) of consecutive laser pulses with different single-pulse energies (E_p), different pulse durations, different beam diameters, different water spray conditions and different Erbium laser wavelengths. The large range of Erbium parameters was used in order to be able to compare volumes of cavities with different diameters, depths and shapes.

Volumes of ablated cavities, V_{tri} and V_{mic}, were then obtained for each cavity using both the laser triangulation method [17-19] and the focusing optical microscope (Leica, M205C) method [6].

III. RESULTS

The measured volumes (V_{tri}) using the triangulation technique in comparison to volumes (V_{mic}) as calculated from the focusing microscope data are shown in Fig. 1 below.

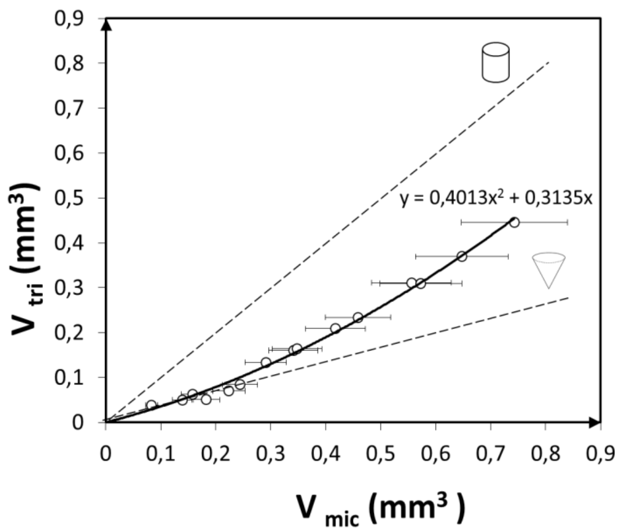

Fig. 1: Measured relationship between volumes V_{mic} as calculated from focusing microscope data, and volumes V_{tri} as obtained using the laser triangulation technique. Doted lines represent relationships as would be expected for cylindrically (upper dotted line) and conically (lower dotted line) shaped craters.

IV. DISCUSSION

Our measurements demonstrate that the relationship between volumes V_{tri}, as obtained using the focusing microscope data, and volumes V_{mic}, as obtained using the laser triangulation technique can be approximated by the following function:

$$V_{tri} = 0.4(V_{mic})^2 \times 0.3\, V_{mic} \quad (1)$$

Figure 1 shows that shallow craters have approximately conical shape while deeper craters approach a more cylindrical shape.

As an example, we consider a previously published study of ablation efficacies in enamel under spray conditions (32 ml/min) as measured using the microscope technique [6]. Ablation efficacies of AE_{mic} = 0.086 mm^3/J and AE_{mic} = 0.080 mm^3/J were obtained respectively for the SSP and SP Er:YAG laser modes (see Fig. 4 in [6]). In this study, craters were drilled with N = 10 consecutive pulses having a single pulse energy of E_p = 0.3 J, with the resulting total delivered laser energy per cavity of E = N x E_p = 3 J. The "cylindrical" volumes, $V_{mic} = AE_{mic}$ x E of the measured craters were therefore V_{mic} = 0.252 mm³ and V_{mic} = 0.240 mm³ for the SSP and SP mode, respectively. Using Eq. 1, the corresponding actual crater volumes were V_{tri} = 0.101 mm³ and V_{tri} = 0.095 mm³ for the SSP and SP modes, respectively. The actual ablation efficacies ($AE_{tri} = V_{tri}/E$) were therefore AE_{tri} = 0.035 mm³/J (SSP mode) and AE_{tri} = 0.031 mm³/J (SP mode). These values agree well with published Er:YAG laser ablation efficacies in enamel [19], obtained under the same conditions (N = 10, E_p = 0.3 J, water spray flow = 30 ml/min) using a triangulation technique, of AE_{tri} = 0.038 ± 0.05 mm³/J (SSP mode) and AE_{tri} = 0.032 ± 0.05 mm³/J (SP mode) (see Fig. 8 in [19]).

V. CONCLUSIONS

A relationship between laser ablated volumes in enamel as measured using the focusing microscope technique and the triangulation technique was obtained. It is demonstrated that this relationship can be used to compare Er:YAG ablation efficacy data from different studies regardless of the experimental technique used. Our study also shows that the shapes of shallow craters are approximately conical while shapes of deeper craters are between a conical and a cylindrical shape.

Disclosure

Both authors are currently working also for Fotona, Slovenia.

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