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High speed imaging of an Er,Cr:YSGG laser in a model of a root canal

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ABSTRACT
Laser systems of various wavelengths and pulse characteristics have been introduced in dentistry. At present, the range of applications for the different systems is being investigated mainly differentiating between soft and hard tissue applications. For the preparation of root canals both hard and soft tissues are involved. Ideally, one would like to use one laser system for the whole treatment.
In this study, we studied the characteristics of the pulsed 2,78 Er,Cr:YSGG laser (Biolase, Waterlase Millenium), in view of root canal cleaning and desinfection. The laser energy was fiber delivered with fiber tip diameters from 400 µm down to 200 µm.
Special thermal and high speed imaging techniques were applied in a transparent model of a tapered root canal and slices cut from human teeth.
High speed imaging revealed the dynamics of an explosive vapor bubble at the tip of the Er laser in water and the root canal model. Typically for Erbium lasers, within a time span of several hundred µs, a longitudinal bubble expanded to maximum size of 5 mm length and 2 mm diameter at 100 mJ and imploded afterwards. In the root canal, the explosive bubble created turbulent high speed water streaming which resects soft tissue from the hard tissue. Thermal imaging showed the dynamics of all lasers heating of the canal wall up to several mm depending on the wavelength and energy settings.
The mechanism of smear layer removal and sterilization in the root canal, is attributed to cavitation effects induced by the pulsed laser. The heat generation into the dentine wall was minimal.

Keywords: Dentistry, Erbium laser, root channel, thermal imaging, high speed imaging.

1. INTRODUCTION
Root canal preparation and treatment has shown to have a variable outcome. In contrast to the nice straight root canals shown in textbooks, the anatomy of the root canal can generally be complex which makes it difficult to reach all cavities with common instruments. This way the smear layer along the canal wall which contains organic and anorganic debris as well as germs and toxins can only be removed partly. The long term results of root channel treatment are very dependent on this structure and the skills of dentist. The outcome can be poor ranging for 40 to 90 %.
In order to improve this outcome, various laser systems has been considered and studied for use in endodontic therapy. The important issues addressed in the studies are bactericidal capacities, removal of the smear layer and thermal safety. In vitro, several lasers systems are shown to be effective for bactericidal effects (1,2,3) and especially pulsed lasers were able to remove the smear layer. The mechanism of action of these lasers is not well understood. Although thermal effects are involved and proved to be safe (4) for most lasers, effectiveness also seemed dependent on the presence on a water spray coolant (3). It is suspected that formation of explosive vapour has a major contribution to the process.
In this study, the mechanism of action of the Er,Cr:YSGG laser, which has shown to be one of the more effective laser in root canal treatment (5,6), was investigated using special imaging techniques.
2. METHODS

Laser system and fiber tips
The laser system investigated was a Er,Cr:YSGG laser from Biolase (Waterlase Millenium, USA) with a wavelength of 2780 nm, at a fixed pulse rate of 20Hz and maximum pulse energy of 300 mJ. The energy is typically delivered through a hollow waveguide to the dental hand piece and at the end transmitted through silica tip with diameter of 200 µm and lengths up to 33 mm. The fiber tip were either submerged under water or positioned into a root canal model.

Figure 1: Biolase Er,Cr:YSGG system with hand pieces containing a short 200 µm silica fiber tip

High Speed imaging set-up:
A high speed imaging technique was applied that has been described in a recent publication by the author (7). The interaction of the laser energy with water and tissue is visualised in real time by capturing images at preset delays from the beginning of the laser pulse to the end of the interaction process in the range of 1 microsecond to 1 millisecond. This is typically the time domain in which the dynamics of cavitation and vapour bubble formation can be observed using pulsed lasers.

Figure 2: optical set-up for high speed imaging
A delay box is programmed to extend the delay at each consequent laser pulse with preset steps of 5 µs up to ms. At captured images are combined to a movie sequence showing the dynamics of interaction of the laser pulse in the range of 1 to 1000 µs. The images have shown to be reproducible where captured at each delay time.

**Root canal model**
A glass cylinder with a lumen a tapered shape was used as a root canal model. The inner diameter was 400 µm at the apex and the length of the canal was 15 mm. The root channel model filled and was submerged under water to prevent interference from air.

![Figure 3: glass tube with artificial root canal](image)

**Experiments**
The high speed imaging was performed using a 200 µm diameter tip submerged in a free water environment and with the tip inserted halfway in the lumen of the root canal model. Video sequences were recorded of vapour expansion and implosion in time range of 10 µs to 1000 µs with typically steps of 10 µs. The pulse energy was varied from 1 mJ to 250 mJ at 20 Hz (0.2 W – 5 W).

### 3. RESULTS

**Erbium laser induced bubble and cavitation dynamics in water**
With the fiber tips submerged in degasified water, video sequences were recorded of bubble expansion and implosion in time range of 10 µs to 1000 µs with typically steps of 10 µs. Figure 5 shows an example of a captured image at high resolution of an expanding bubble. In each image information of the size and delay from the start of the laser pulse was imprinted. These individual images at each delay time can be combined to a sequence as shown in figure 6 showing the dynamics

![Figure 4: video captures of expanding and imploding vapour bubble at from 0 to 260 µs after the onset of 50 mJ laser pulses](image)
The dynamics of the vapour bubble created by the Erbium laser in water is described below. The typical pulse length of the Er,Cr:YSGG laser is around 150 µs depending on energy. In the first tens of microseconds the energy is absorbed in a 2-5 µm layer of water that is instantly turned into vapour. This vapour at high pressure starts expanding at high speed and providing an opening in front of the fiber for the beam of laser light which continuous to evaporate the water surface at the front of the bubble. A longitudinal shaped bubble is formed through the liquid until the pulse ends after about 150 µs. This mechanism has be referred to as ‘the Moses effect in the microsecond region’ (8). At the end of the pulse, the vapour condensates while the momentum of expansion creates a lower pressure inside the bubble. Both mechanisms provoke an implosion of the bubble. Water surrounding the bubble is accelerated to fill in the gap. The bubble implosion starts near the fiber tip, where the expansion started, resulting in a separation of bubble from the tip. The water seems to rush into the bubble from the back making the imploding bubble shaped like a sickle. After about 300 µs the process of implosion is finished and the bubble is vanished. The bubble shapes show to be reproducible at each pulse in a free water environment.

Figure 5: bubble formation starts after the energy during the laser pulse rises above the threshold of vaporization and the bubble starts to collapse going below this threshold determining the size and life time of the bubble depending on energy (inset).
Root channel model

High speed imaging was also applied in the transparent root canal model while exposing the laser with a 200 \( \mu \text{m} \) fiber tip positioned halfway in the canal. The canal was filled with water and the model was submerged in water. The dynamics of bubble growth in the channel compared to the free water situation is illustrated in figure 6. The sideward and forward expansion is limited by the canal wall while the backward expansion is blocked by the fiber making the lumen of the canal even smaller. The individual images at each delay time are combined to the sequence.

![Figure 6: Images of expanding and imploding vapour bubble inside the conical root channel model from 0 to 700 \( \mu \text{s} \) after the onset on 12 mJ pulses.](image-url)
Due to the limited space inside the small canal, the dynamics in the root channel is different compared to the bubble in a free water environment. The dynamics of the bubble inside the canal is described below:

The interaction with the water during the laser exposure turns the water into vapour within the first tens of microseconds. The small canal prevents the vapour to expand freely sideways resulting in a forward and backward expansion in the canal. The first frames of the sequence in figure 6 show an air bubble being compressed to a flat disk. The dynamics of expansion and implosion is delayed compared to the free water situation due to the resistance of the water that has to be displaced in the small canal. The process in the small canal takes about 3 times longer. For higher energies, the canal is totally filled with vapour. After the end of the pulse, the vapour condensates and water is sucked back into the canal from the opening at the top. It takes time before the water has filled all of the gaps and the situation is stabilized. This can take up to milliseconds depending on the pulse energy.

In figure 7 the speed of expansion is in first order approximation determined from video sequences comparing the bubble expansion in free water and the canal. As expected, the expansion speed in the canal is lower due to resistance but still impressive.

![Figure 7](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

**Figure 7**: velocity of expansions determined from the development of bubble length in time in and outside the root channel model.

4. **DISCUSSION**

In this study, high speed imaging enabled the capture of images with microsecond resolution to obtain a better understanding of the effects of the Erbium laser pulses in a root canal model. Although each image is captured from a different pulse of the laser, the dynamics of the bubble formation has proven to be reproducible in the in vitro setting used for this study.

The high speed imaging has provided sufficient data to attribute the ‘cleaning’ effect of the Erbium pulses in a root canal to cavitation effects from explosive vapour bubbles. In a clinical setting, this vapour will also spread through potential secondary root channels reaching places where normal mechanical instruments are unable to come. The ‘hot’
steam has potentially a superficial sterilization effect. The implosion of the vapour bubble and the high speed fluid displacements exert forces on the smear layer along the canal wall and might resolved it. It is known that the high speed fluid displacement along a surface can create secondary cavitation effects at irregular places. The implosions of these cavitations will be focussed on the irregularity. This mechanism could also contribute to the effectiveness of lasers in root canal treatment.

Since explosive vapour and cavitation can only exist in the presence of water, the use of a water spray is important for the efficacy of the treatment. Performing the procedure without water, the mechanism of action will be more attributed to thermal effects with potential adverse effects due to deeper heat penetration into periodontal ligament and the bone tissue along the root surface. The water spray will provide effective cooling and protection.

5. CONCLUSIONS

High speed imaging has shown to be useful to obtain a better understanding of the mechanism of action of microsecond pulsed laser in the treatment of root canals

The mechanism of action during root canal treatments with Erbium laser pulses is attributed to rapid expanding and imploding steam bubbles that have a superficial sterilization effect in combination with high velocity water displacements along the canal wall which removes the smear layer.

REFERENCES