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Correlation of vibrometry and cleaning effects in ultrasonic dental instruments

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ABSTRACT

One application of physical acoustics is the development of ultrasonic dental instruments for cleaning purposes including descalers and endosonic files. The vibration characteristics of these instruments have been measured by scanning laser vibrometry, SLV. One possible contribution to the cleaning processes is cavitation and we have been using sonochemical methods to characterize cavitation around dental instruments. For example, significant amounts of sonoluminescence can be produced at the vibration antinodes of the endosonic files and there is good correspondence between regions of cavitation and large vibration. The cleaning efficacies of the files were studied using an irrigant used in endodontics (sodium hypochlorite) to bleach a dye (Rhodamine B). Results showed that ultrasound accelerates the rate of degrdation of the dye. For a range of different file shapes and sizes, there was a correlation between sonoluminescence and Rhodamine B degradation although the chemical effects of each files depended on their design. A comparison of the chemistry with the SLV results should allow the optimization of cavitation production along the endosonic files by modifying their shape to increase the cleaning efficacy for benefit in treatments.

INTRODUCTION

One of the major processes where ultrasound is used for industrial processing is in cleaning. A typical application is in the cleaning and sterilization of medical instruments. Cavitation is well known as a major factor playing a key role in ultrasonic cleaning. [1] One contribution of ultrasonic cavitation in cleaning arises from the removal of insoluble impurities from the surface of the object to be cleaned [2] due to, as shown by Crum, the development of microjets from cavitation bubbles in solution and close to the surface being cleaned. [3] In addition, the formation of radicals during the collapse of cavitation bubbles [4] also contributes to antibacterial properties as highly reactive OH• radicals tend to destabilize bacteria and other cells hence resulting to oxidative damage in bacteria [5-7] and aiding sterilization.

As a further application of cavitation activity in cleaning, ultrasound was introduced into dentistry for similar reasons. One of the earlier applications of ultrasound in dentistry was in the early 1960s, when it was used for mechanical debriment during tooth descaling, the removal of calculus and deposits from tooth surfaces. [8] Since then, it has been reported that there were adequate removal of calculus by using ultrasonic tips [9] at shorter treatment times [10] compared with more conventional, manual scaling methods.

In the late 1980s and 1990s, the nature of cavitation and acoustic microstreaming began to interest many researchers in periodontal cleaning in dentistry, [11] as it was found that ultrasonic treatments on tooth descaling had also resulted to formation of sonochemical products apart from the usual mechanical cavitational effects. [12] Further investigations were carried out by several researchers on the sonochemical effects on dental descalers [13] and have shown that the sonochemical effects aided the cleaning process on the tooth surfaces and that they could be correlated with the motion of the instruments and that the design of the instrument influenced the amount and spatial distribution of the cavitation that was produced. [14]

Similar to the dental descalers, it has been reported that cavitation occured at high powers on endosonic files used for endodontic (root canal) treatments. [15] Here, the purpose is to remove debris and infected tissue from the root canal of the tooth. However it was also suggested that there were no significant differences between cavitation and non-cavitational technique in the cleaning process. The lack of study in this area brings the need to characterize, investigate and evaluate the characteristics of these dental instruments in order to optimize and provide a better next generation of these instruments.

In order to initiate our study on dental instruments, areas of cavitation activity have been as mapped based on the reaction of OH• radicals with luminol giving out short-intense blue light known as sonochemiluminescence, when cavitation bubbles collapse. [16] This method, as well as the measurement of chemical effects, has been applied to several different dental tips to get a reliably correlated set of results, which were then compared to the vibrational characteristics of these dental instruments measured by scanning laser vibrometry (SLV) to evaluate the relationship between ultrasonic driven vibration displacements and the areas of cavitational activities. [17-18]

Further, a study on the efficiency of sodium hypochlorite – a common irrigant used in dental practices [19-23] – was assessed by looking at its bleaching effectiveness in the presence of ultrasound of the OCl^- ion. [24-25] A sample dye, Rhodamine B, was used for this purpose, as several studies of degradation of Rhodamine B have been carried out previously and showed that ultrasound accelerates its rate of degradation. [26-30]

Given the widespread use of Rhodamine B, its bleaching by hypochlorite has been used in this work to characterize the effect of ultrasound on the reaction using a dental endosonic system for different tips and thereafter compare and correlate to the vibration performance as well as the cavitation activity around the dental tips.

EXPERIMENTAL

All experiments were conducted using a miniMaster ultrasound generator provided by Electro Medical Systems, Nyon, Switzerland, operating at a working frequency of ~30 kHz. This consists of a piezoelectric transducer held in a handpiece into which a metallic tip is fitted. The different tip designs (each is ca. 12-15 mm in length) used are shown in Figure 1. All experiments were repeated three times to assess consistency and reproducibility. All reagents were analytical grade, obtained from Sigma-Aldrich Co., UK, unless otherwise stated, and were used as received. The power output of the generator would hereafter be referred to as power 1, 5 and 10; indicating the arbitrary power units of low, medium and high power sonication on the generator.

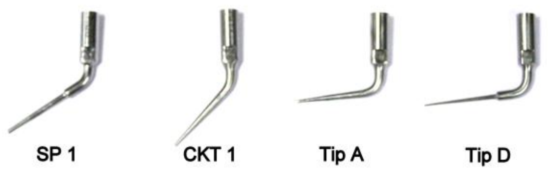

Figure 1. Dental endosonic tips used.

Calorimetry

Calibration of all dental tips is essential to ensure a standardized power output is obtained for comparable results. [31] In order to achieve this, calorimetry of the dental tips was performed, by measuring the temperature rise over five minutes when an operating dental tip was immersed into 50 cm^3 of distilled water in a beaker at different power settings on the generator (1-10).

Upon sonication for five minutes, the final temperature of the solution was noted and the total power output of the system, Q, was calculated from:

$$Q = \frac{mC_p\Delta T}{t}$$

where m is the mass of water (kg), C_p is the specific heat capacity of water (kJ kg^{-1} K^{-1}) and , ΔT: the temperature difference (K) over a time period t (s). The intensities produced by each of the tips could then be estimated by dividing the power output by the emitting area of the dental tips, obtained through image analysis with the aid of ImageJ software and geometrical calculation. [32]

Luminol photography

Cavitation activity around the dental tips was mapped by monitoring luminescence emission from luminol solutions consisting of 1×10^{-3} mol dm^{-3} luminol (5-amino-2,3-dihydro-1,4-phthalazinedione), 1×10^{-4} mol dm^{-3} hydrogen peroxide and 1×10^{-4} mol dm^{-3} EDTA (ethylenediaminetetraaceticacid), prepared in deionized water and made up to pH 12 by the addition of sodium hydroxide. [16]

A dental tip was immersed in 50 cm^3 of luminol in a glass cuvette (5 cm × 2.5 cm × 10 cm). A digital single-lens-reflex camera (Canon EOS 500D) with a Canon EF-S 60mm f/2.8 USM Macro lens mounted, was placed aligned to the position of the tip and set to ISO 3200 for close-focus, light-sensitive measurements. The focal distance was adjusted to give a 1:1 reproduction. Images were taken in a light-proof box, over exposure times of five minutes, both with and without sonication. The procedure was repeated for all dental tips at powers 1, 5 and 10. The intensity of the luminol emission was calculated using ImageJ [32] with background image subtraction.

Fricke dosimetry

Fricke dosimetry [33] was performed at each power used to detect the amount of OH• radicals produced during sonication based on oxidation of Fe(II) to Fe(III). 20 cm^3 of Fricke solution (0.001 mol dm^{-3} $FeSO_4.7H_2O$ and 0.005 mol dm^{-3} H_2SO_4) was placed into a beaker, and the absorbance of the solution was noted every 5 minutes during operation for 30 minutes using an Agilent 8453 UV-vis spectrometer at 304 nm.

Scanning laser vibrometry (SLV)

The vibrational movement of the dental tips was measured as described previously by Lea, et. al. [18]. The SLV system was a PSV 300-F/S from Polytec GmbH, Polytec-Platz, Waldbronn, Germany and used a class II, He–Ne laser operating at 632.8 nm. A dental tip was clamped firmly with the tip facing downwards, with the laser beam focusing at various points along the tip. Motion along the plane of the tip was measured, displayed as the tip displacement, vibration velocity and the vibrating frequency. Scan points were spaced out equally along the working length of the dental tips (12–15 mm). The maximum displacement of the tip at each scan point was measured and the average of five cycles was recorded for each tip, at each power setting.

Degradation of Rhodamine B

The cleaning efficiencies of the dental tips were evaluated based on decolourisation of Rhodamine B (5 mg dm^{-3}) with and without the presence of 2% sodium hypochlorite solution. Changes in the concentration of Rhodamine B were monitored by measuring the absorbance at 554 nm on an Agilent 8453 UV-visible spectrometer, upon sonication for 30 minutes in quartz cuvette (4.5 cm × 1.25 cm × 1.25 cm) at generator powers 1, 5 and 10.

RESULTS AND DISCUSSION

Calorimetry

Table 1 shows the surface area estimated over the working length (i.e 12–15 mm) of the different tips used as well as their respective highest intensity. Figure 2 shows the sound intensity for the three different powers used for all four tips. It clearly demonstates a significant difference in the intensity depending on the tip design (shape and size) even though all were operated on the same arbitrary setting.

SP 1 appeared to be the most efficient dental tip, with the highest intensities at medium and high settings. There was no significant difference ($p>0.05$) in power output at the lowest power setting as the temperature rise was very small.

Table 1. Surface area and maximum intensity for various tips

Tip	SP 1	CKT 1	Tip A	Tip D
Surface Area (cm^2)	0.310	0.440	0.474	0.182
Intensity at "Power 10" ($W\ cm^{-2}$)	10.426	4.460	3.270	11.502

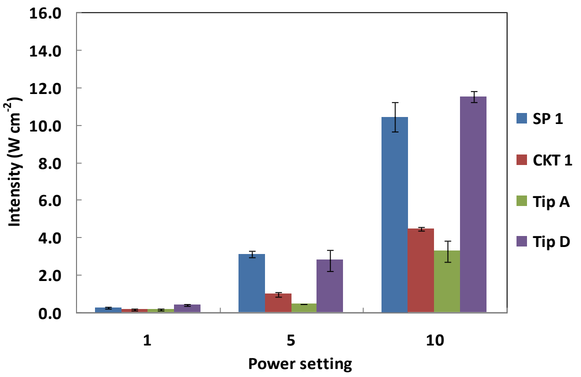

Figure 2. Ultrasound intensities for different dental tips at generator powers 1, 5 and 10.

Luminol photography

Hydroxyl, OH• radicals are produced due to breakdown (sonolysis) of water molecules caused by the very high temperatures generated during the collapse of cavitation bubbles. These OH• radicals react with luminol, producing short-lived intense blue light from chemiluminescence. Luminescence photography was used to map the areas of cavitation by capturing the images of sonoluminescence when a dental tip is immersed in luminol, as shown in Figure 3. Image analysis was performed with the aid of ImageJ software to evaluate the average emission intensity across a fixed area around the working length of the dental tip. Figure 4 shows the collated results of the luminol emission produced during sonication for each of the tips at each power used. SP 1 showed the highest cavitation activity, followed by Tip A, CKT 1 and finally Tip D. The reason for the lack of cavitation activity around Tip D despite high intensity delivered to the tip could be due to the fine design of the tip with a narrow low diameter. This may result in the tip passing through a fluid while causing relatively low disturbance of the liquid, hence resulting in insufficient negative pressures to produce cavitation during ultrasonic oscillation. A similar effect was reported for ultrasonic descalers [34].

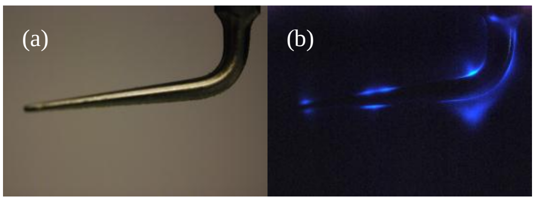

Figure 3. (a) Normal photograph of a dental tip immersed in luminol; (b) Luminescence photograph (luminol emission) of dental tip A on exposure for 5 minutes.

Fricke dosimetry

In Fricke dosimetry, the initial aqueous Fe^{2+} solution was oxidized [33] to Fe^{3+} based on the reaction:

$$Fe^{2+} + OH\bullet + H^{+} \rightarrow H_2O + Fe^{3+}$$

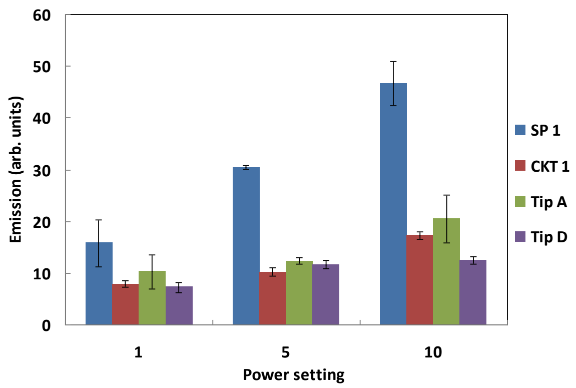

Figure 4. Sonochemiluminescence emission from luminol solutions with different dental tips at generator powers 1, 5 and 10 upon 5 min exposure.

Fe^{3+} was then detected photometrically at 304 nm using a UV-visible spectrometer. The rate and extent of reaction gives a measure of the total oxidizing ability of sonochemical systems. The final absorbance of Fe^{3+} for each dental tip was collated and shown in Figure 5. The results showed fairly good correlation between the production of sonoluminescence and the production of Fe^{3+} upon sonication, (Pearson's correlation coefficient, $r = 0.8$; sample size = 9; critical value of significance = 0.582) with SP 1 giving the highest Fe^{3+} absorbance at power 10 and Tip D producing the least. There was no significant difference ($p>0.05$) in absorbance at lower power settings due to the very low extent of reaction causing small changes in absorbance (except for Tip D: $p = 0.049$).

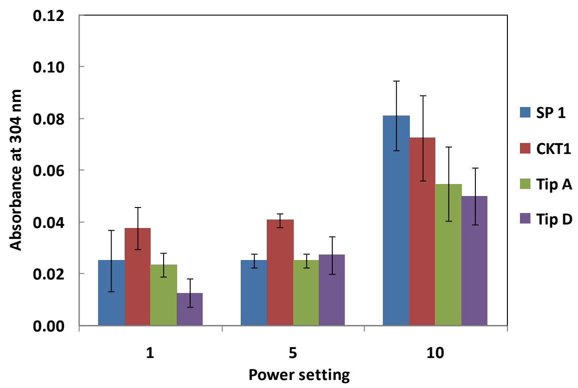

Figure 5. Absorbance of Fe^{3+} at 304nm upon sonication for 30 min at generator powers 1, 5 and 10.

Scanning Laser Vibrometry

An example of the displacement profile of a dental tip during operation is shown in Figure 6. The results showed good correlation between the areas of maximum displacement (antinodes) to the areas where cavitation activity occurred, based on luminol mapping (see Figure 3). The results showed that the maximum vibration displacement amplitude always occurred at the end of the tip, similar to that reported in our previous work on dental descalers. [34] This however does not correspond with the region of maximum cavitation as noted above. As expected, the displacement amplitude increases with rising power setting.

The maximum displacement amplitudes for each tip are shown in Figure 7. Again, there is a reasonable correlation with the luminol emission results (Pearson's correlation coefficient, $r = 0.91$; sample size = 9), suggesting that the vibrational motion of the dental tips depends on the amount of energy transferred to it, with SP 1 having the highest vibrational displacement, followed by Tip D, Tip A and CKT 1 respectively. However, the transfer of energy to the system and the vibrational motion were not the sole factors affecting cavitation production. This explains the difference between SP 1 and Tip D despite both producing large displacement amplitudes.

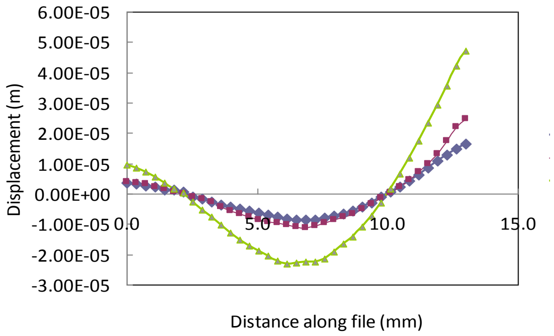

Figure 6. Vibration displacement profile of SP1 along the file at generator powers 1, 5 and 10. ◆ Power 1; ■ Power 5; ▲ Power 10

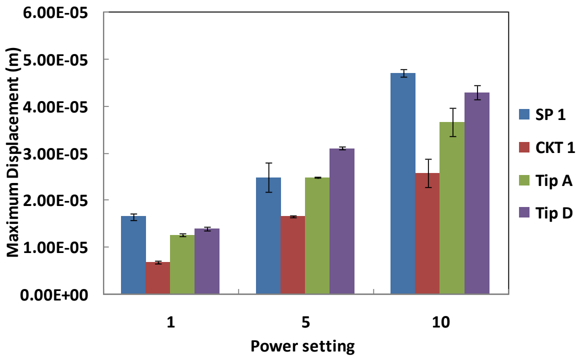

Figure 7. Maximum vibration displacement (m) of all tips at powers 1, 5 and 10.

Degradation of Rhodamine B

Figure 8 shows the rate of degradation of Rhodamine B upon sonication at different powers. The rate of degradation was low but significant ($p<0.05$) when Rhodamine B solution was sonicated at power 10 without the addition of any reagent. The presence of 2% NaOCl in the solution accelerated the reaction significantly, with increasing rate and extent of degradation as the power increased. Almost all Rhodamine B has been degraded in 30 minutes upon sonication at the highest power.

As expected, due to the vast excess of NaOCl, a *pseudo*-first order reaction was obtained, as shown in Figure 9 so that rate constants could be evaluated to facilitate comparison between tips and the effect of varying the experimental conditions.

The collated results in terms of the final percentage of degradation of Rhodamine B after 30-minute treatment, is shown in Figure 10. At the highest power, both Tip A and SP 1 showed the most degradation, followed by CKT 1 and Tip D. This, again, could be correlated to cavitational activities. The production of radicals aided in breaking the double-bonds on the the chromophore of Rhodamine B, causing it to degrade and so change its optical properties.

Further Discussion

This work above has shown that larger amounts of cavitation are produced at higher powers as judged by luminol emission and the production of Fe^{3+}, both measures of the oxidizing power due to radical production in the system. However, the SLV result showed that the point of maximum vibration always occurs at the end of the dental tip whereas cavitation is rarely detected there. This outcome is similar to our previous work on dental descalers [34] where cavitation activity at the end of dental descaler was not great even when it was vibrating at its resonant amplitude. This could be due to the shape of the dental tips; as all endosonic tips have circular cross-section, resulting in ineffectiveness at displacing solvents to produce sufficiently high negative pressure around the ends. Hence, further work on characterizing fluid motion around dental tips is essential in order to strengthen our claim stated above.

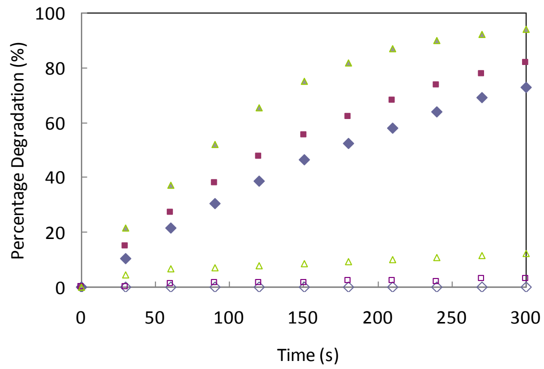

Figure 8. Percentage degradation of Rhodamine B in the presence of ultrasound at various generator settings. ◊, ◆ Power 1; □, ■ Power 5; Δ, ▲ Power 10

Closed symbols – 2.0 wt% NaOCl solution ; open symbols – no NaOCl

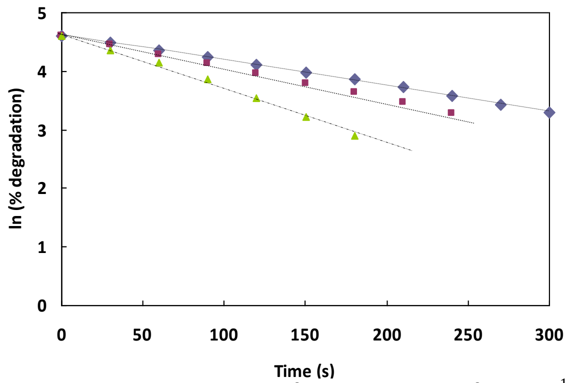

Figure 9. First order rate plot for the bleaching of 5 mg L^{-1} Rhodamine B with 2% sodium hypochlorite. ◆ Power 1; ■ Power 5; ▲ Power 10

As for the results obtained for the degradation of Rhodamine B, there was a poorer correlation than with the luminol mapping and Fricke dosimetry results (Pearson's correlation coefficient, $r = 0.557$; sample size = 9; critical significance value = 0.582) indicating that other factors are at play. It has to be noted that vibrational motion of the dental tips could also contribute to decolourization of Rhodamine B in addition to chemical effects from ultrasonic cavitation activity. This difference is acceptable as in normal dental practices, ultrasonic instruments were used not solely for its ultrasonic chemical effects. [8-15] Therefore, slight discrepancies in the results are not significant in terms of clinical practice although their further investigation is underway to investigate the fundamental properties of each of the processes involved so that optimum designs of dental tips can be designed and manufactured.

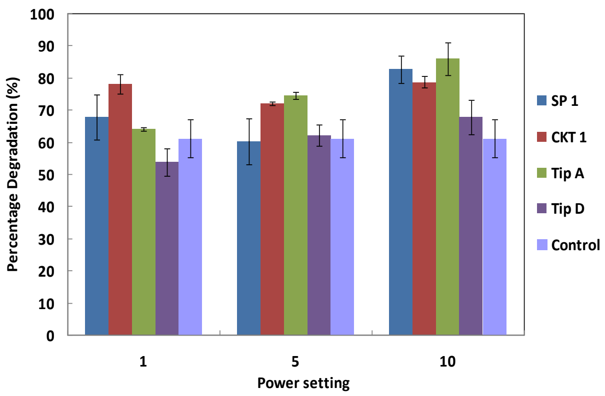

Figure 10. Percentage degradation of Rhodamine B after 30 minutes of sonication on various dental tips at generator powers 1, 5 and 10 (Control = no sonication).

CONCLUSIONS

Different tips designs result in different power outputs which further influence the vibrational movement of the tips, cavitation activity and the rate of degrading Rhodamine B. A fairly good correlation could be obtained from between cavitation activity, SLV and the cleaning efficiency based on the rate of degradation of Rhodamine B.

Overall, the SP 1 tip appears to be most effective design of those investigated, and this has a very strong relationship between the total energy transferred to the tip and also the shape of the tip.

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