Mapping Cavitation activity around dental ultrasonic tips

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Field

Abstract

Objectives: Cavitation arising within the water around the oscillating ultrasonic scaler tip is an area that may lead to advances in enhancing biofilm removal. The aim of this study is to map the occurrence of cavitation around scaler tips under loaded conditions.

Materials and Methods: Two designs of piezoelectric ultrasonic scaling probes were evaluated with a scanning laser vibrometer and luminol dosimetric system under loaded (100g/200g) and unloaded conditions. Loads were applied to the probe tips via teeth mounted in a load measuring apparatus.

Results: There was a positive correlation between probe displacement amplitude and cavitation production for ultrasonics probes. The position of cavitation at the tip of each probe was greater under loaded conditions than unloaded and for the longer P probe towards the tip.

Conclusions: Whilst increasing vibration displacement amplitude of ultrasonic scalers increases the occurrence of cavitation, factors such as the length of the probe influences the amount of cavitation activity generated. The application of load affects the production of cavitation at the most clinically relevant area – the tip.

Clinical Relevance: Loading and the design of ultrasonic scalers lead to maximising the occurrence of the cavitation at the tip and enhance the cleaning efficiency of the scaler.

Key Words: tooth cleaning, periodontology, ultrasonic scaler, vibration, cavitation

Introduction

Ultrasonic scaling is a common procedure undertaken by dental health professionals. The aim is to disrupt the bacterial biofilm and remove calcified deposits from the teeth [1, 2] either subgingival (below the gumline) or supragingival (above the gumline). Various designs of scaler exist but they all involve a metal 'tip', which contacts the tooth and is driven at ultrasonic frequencies by a transducer housed in a handpiece, which the dentist manipulates. A stream of water flows over the tip to prevent frictional heating and also to wash debris from the treatment site. Clinicians have identified cavitation arising within the water around the oscillating ultrasonic scaler tip as an area that may lead to advances in enhancing the cleaning process [2].

Cavitation is the formation and explosive collapse of microscopic bubbles (cavities) when the acoustic pressure during rarefaction becomes more negative than the saturated vapour pressure of the liquid. Collapse of these bubbles results in localised extreme conditions of pressure and temperature, up to 5000 K and 500 bar, which can lead breakdown of water and production of reactive species such as radicals inside the bubble [3]. In addition, collapse near a surface results in microjets that impact on a surface and aid surface cleaning [4]. This is the primary effect in, for example, ultrasonic cleaning baths [5].

We recently demonstrated that cavitation could be both detected and quantified around scaler tips working in air [6, 7]. The production of free-radical species arising from cavitation bubbles was correlated with the vibratory motion of the tips as determined by scanning laser vibrometry. The work showed that, contrary to expectation, the maximum cavitation did not occur at the free end of the tip, even though this corresponded to the highest degree of motion as measured by vibration amplitude. Higher levels of cavitation were measured around regions further up the probe towards its bend at a vibration antinode. It was found that the design of the tip affected both the spatial and temporal distribution of cavitation. It would be clinically advantageous if the cavitation occurrence were maximised at the contact area between the working tip and the tooth surface.

Our previous work involved the scaler probes simply immersed in water. Under clinical conditions, the tip is under a load via contact with the tooth rather than being free to oscillate. The vibratory motion may therefore be constrained by the load [8], which may in turn alter the onset and intensity of cavitation. The hypothesis of this investigation is that the vibration characteristics and occurrence of cavitation around scaler tips under loading is comparable with those used in clinical practice.

Materials and Methods

Ultrasonic scalers

A piezoelectric miniMaster Ultrasonic generator was used to generate the tip movement. Both A and P scaler tips were selected which have different lengths A-17mm/P-20mm but similar widths. The scaler tips oscillate with a nominal frequency around 30 kHz. Only one tip of each design was used for these investigations. Power settings for the miniMaster generator were selected from a control panel and are expressed as the fraction of the maximum available (i.e. 1/10, 5/10 and 10/10).

Each scaler tip was contacted against the surface of an extracted molar tooth mounted in epoxy resin with the top half exposed using the configuration shown in Figure 1. The contact with the surface of the tooth was at an angulation of approximately 10 degrees with the last 2mm put against the root surface of the tooth, which was checked with a stereomicroscope and contact area marked to allow reproducibility. A Model 131 (100N) load cell (Sensotec, Columbus, OH, USA) connected to an E725 microprocessor transducer indicator / controller was used to control the contact force between the edge of the scaler tip and the tooth. For this work, force equivalent to either 1 or 2 Newtons (with a precision of ± 0.01 N) was used; these being comparable with those generated during use by a clinician [9, 10]. The arrangement was contained in a container with transparent plastic walls that could contain 50 cm^3 of liquid.

Vibration analysis

The vibrational motion of each probe was analysed using a scanning laser vibrometer (PSV 300-F/S, Polytec GmbH, Polytec-Platz, Waldbronn, Germany). Briefly, the technique measures the Doppler shift of a laser beam that is reflected off the target surface, giving the velocity of the surface with respect to the incident beam [10, 11]. The scaler tip was clamped into a reproducible position and fully immersed in water. The laser vibrometer was positioned to enable the longitudinal component of the probe oscillation to be measured. It is known that ultrasonic scaler probes oscillate in an elliptical manner [12]. However, for the purposes of this study, the larger longitudinal motion was used as a measure of the performance of the scaler probe. A number of equally-spaced scan points were chosen along the length of each tip, from the free end to as close to the handpiece as could be measured. The maximum displacement of the tip at each scan point was measured and the average of ten cycles was recorded for each tip, at each set of conditions.

Cavitation analysis

All reagents were analytical grade and obtained from Sigma-Aldrich Co., UK, unless otherwise stated, and were used as received. Cavitational activity was monitored by detecting the luminescence emission from a luminol solution 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 a deionised water solution and made up to pH 12 with the addition of sodium hydroxide [6]. Luminol sonochemiluminescence occurs through reaction with hydroxyl radicals formed through the dissociation of water during cavitation and is a sensitive indicator of the presence and spatial distribution of cavitation in aqueous solution [13].

The scaler tip was fixed in position as above and immersed in 50 cm^3 of luminol solution. An Artemis ICX285 charge coupled device camera (Artemis CCD Ltd, Norwich, UK) with a 35mm focal length lens and f2.8 aperture was used in conjunction with a low light CCD ICX285AL imaging sensor to acquire photographs of the anterior surface of the probe. The apparatus was sealed in a lightproof box, and light emission recorded for 60 seconds of scaler operation. The procedure was repeated for each setting with the luminol solution replaced in each case. Daylight photographs were also taken. The total intensity of the luminol emission was calculated after subtraction of background levels using 'ImageJ' software [14] which integrated the total emission over the exposure time.

Statistical Analysis

Data were analysed using SPSS v12.0 (SPSS, Chicago, IL, USA). The significance of variation in true tip displacement amplitude under various load conditions and generator power settings, was tested using univariate analysis of variance (General Linear Model) and using multiple post-hoc comparisons (Tukey test) at a significance level of $p < 0.05$, with the dependent variable being displacement amplitude.

Results

Vibration data

The A tip had a fundamental oscillation frequency of 28.88 kHz. The maximum displacements of each point along the A tip when operated at maximum power at several loads between the tip and the tooth surface are shown in Table 1 and Figure 2a. There is a node 4.4 mm from the end of the tip where no vibration takes place and the highest displacements were seen at the free end of the tip. Operation under loaded conditions damped the vibrations and the maximum amplitude was reduced under these conditions by up to 50% at the higher loading ($p < 0.0001$). Similar observations were seen with the P tip which had a much thinner design (Table 1). It operated at a fundamental frequency of 29.25 kHz, two nodal points were observed at 2.2 mm and 7.2 mm from the free end of the tip (Figure 2b). While some damping effects were noticeable as a result of contact loadings, this was less than with the A tip and amounted to only 10 – 15 % of the motion of the free end of the unloaded tip. Neither the position of the antinodes or the magnitudes of the displacements were significantly different when the scaler was used under load.

Cavitation around scaler tips

Chemiluminescence emission occurs when a hydroxyl radical, in this case generated by sonolysis of water during cavitation reacts with luminol. Emission is in the visible part of the spectrum and, though faint, can be readily photographed to illustrate the spatial occurrence of cavitation and is illustrated in Figure 3 for the two tips studied. Some qualitative trends are seen such as increased emission at higher powers, differences in emission due to the effect of load and concentration of cavitation production in certain areas of the tip rather than uniformly along its whole length. In order to quantify these effects, a measure of the amount or degree of cavitation is required. The lifetime of the luminol excited state is much shorter (of the order of milliseconds) than the exposure time over which data was collected so that the integrated emission intensity gives this measure of the total cavitation activity. A background image, recorded for 60 s with the apparatus assembled but the scaler not switched on, was taken and subtracted from images recorded during operation of the scaler. An area (620 pixels × 560pixels) was defined in the software to include the whole area over which emission occurred and the same area used for all images with a particular type of tip. The total emission intensities measured are shown in Figure 4 for the two tips.

For the A tip, operation under load raises the power needed to generate significant amounts of cavitation. For zero loading, emission is seen at a power of 1/10 and there is a small amount that is seen at the tip when operated in contact with the tooth (Figure 3a). The cavitation is visible at the bend unloaded at 3/10 power. The intensity of the luminol emission increases at the bend at power settings of 5/10 and above. The results for the P tip follow similar trends (Figure 3b) and cavitation activity increases at high power setting and loading both at the contacting end and at the bend of the probe. With no contact at 5/10 there is a focus of cavitation at the bend and this is clearly seen for all settings at 5/10 and above. Qualitatively there is more cavitation focussed towards the tip of the probe.

Low levels of emission – and hence cavitation – do occur at low power even though they are not visible in the photographs following measurements from the image analysis (Figure 4). The cavitation activity is reduced on contact with the tooth which is greater when operated at the higher powers. This parallels the reduction in vibration amplitude measured by SLV. However, it is notable that at the lower power settings, emission increases with load. The P tip also produces an increase of cavitation with increasing load but in contrast to the A tip this is unaffected by loading (Figure 4). There is a small increase with loading of 2 N over the unloaded condition.

Discussion

The occurrence of cavitation may, in part, be correlated with the vibration amplitude of the scaler tips. The first stage in the current study was to detail the effect of loading on the vibration amplitude and then to relate this to the occurrence of cavitation. The tips chosen represent two opposite designs in length making the A tip relatively broad in comparison to the P tip. The largest motion is generated at the tip (Figure 2) which is reduced on loading affecting the A tip more in comparison to the P tip especially at the free end of the scaler. Loading of the scaler tips does not markedly change their oscillation characteristics and the positions of the antinodes did not change significantly. In this study loading was confined to the tip. Future work is necessary to determine whether the amount of cavitation produced would change at different loading points along the probe. As the tip is operated in the subgingival environment the contact may not always occur where the clinician assumes it to take place. The cavitation may be increased in such a confined area.

The occurrence of inertial cavitation agreed with the maximum displacement amplitude values, especially at the anti-nodes of the probes (Figure 3). Despite the maximum displacement amplitudes occurring at the end of the tips, the highest cavitational activity was generated at the anti-node positions of both tips (Probe P had two antinodes). These values increased with higher generator power settings and were reduced with greater contact loadings. The generation of the cavitation is complex and displacement amplitudes may not be the only factor in the generation of inertial cavitation. Further research is required to detail how the shapes and designs of ultrasonic scaling tips influence the generation of inertial cavitation.

The A probe generated the most inertial cavitational activity under both unloaded and loaded operating conditions. The A probe is broader in cross section whilst the slimmer P tip has a different motion of vibration (Figure 2) with a first node is closer to the tip. This leads to more cavitation produced closer to the tip and at the range of displacement amplitudes produced is not affected by loading. In summary, the A probe produces more cavitation but the P probe produces it closer to the tip. Clinically this will be more of benefit as it is the tip, which will be working within the periodontal pocket. The production of cavitation especially during contact with a tooth is a complex phenomena and the design of the probe has a great influence on it occurrence.

This study suggests that vibration displacement amplitude is not the only factor, which affects cavitation production around a scaler probe, despite being shown previously to be significant [6, 7]. Scaler design is an important consideration in the generation of cavitation and the physical probe dimensions and contact with a surface may also be contributing factors that outweigh the effect of increased displacement amplitude. In this investigation only one tip of each design was used at the different settings. It is possible that the range of probe designs available to the clinician will lead to different oscillation patterns leading to a range of cavitation production. Another variable to consider is the temperature of the water, which in this study was set at room temperature. Further work is merited to determine whether the temperature of the water affects cavitation occurrence.

Our previous work showed cavitation occurred along the length of the probe [7]. These qualitative results show that when cavitation is mapped then some will occur at end of the probe during loading and alhough the pattern varies around the tip, its occurrence will be useful clinically. For the first time we have shown that cavitation occurs near to the tip of the probe under loading and that the design of instrument has a large influence on the amount produced. This has clinical implications as the cavitation can be put to good use during use although clinical trials are needed to determine its fill impact. The results inform how the tips may potentially be modified leading to more cavitation and the potential for improved clinical effectiveness. This will be the subject of future research as we wish to see if the cavitation may be used to increase measures to disrupt the biofilm that is the main causative factor in the disease process

Conclusions

This work has shown that cavitation can be produced and measured around clinical ultrasonic scalers working under loads typical of those involved in clinical practice. The loading changes the distribution of cavitation in water from mainly at bend to more occurring at the tip. These findings may lead to changes in the design of instruments to maximise the occurrence at the tip and enhance the cleaning efficiency of the scaler.

Acknowledgments

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The authors declare that they have no conflict of interest.

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Legends for Figures

Figure. 1 Diagrammatic representation of the positioning of the ultrasonic probe against teeth set in resin

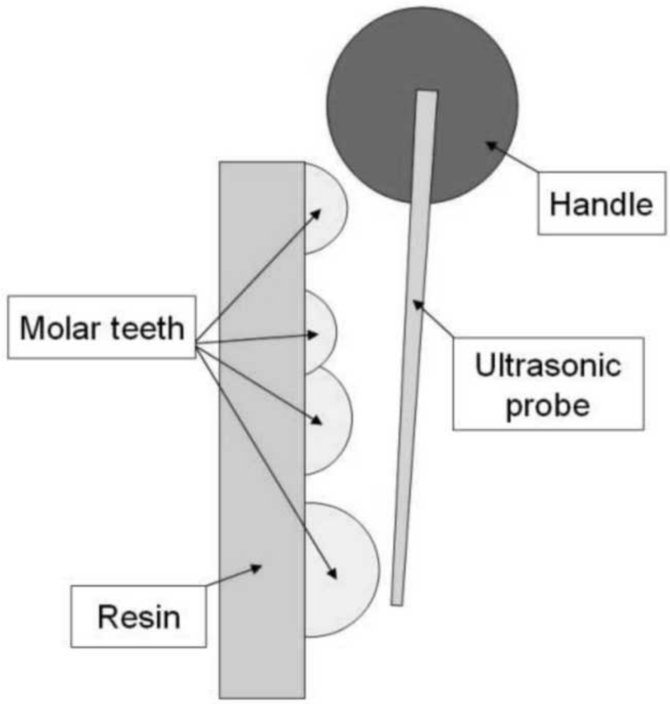
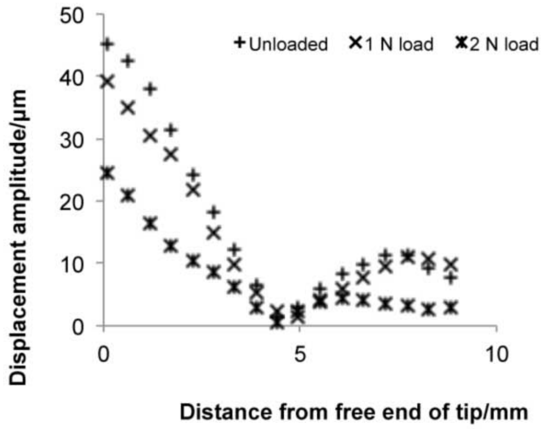


Figure 2 Displacement amplitude for the loaded A probe (a) and P probe (b) at 10/10 generator power settings.

(a)



(b)

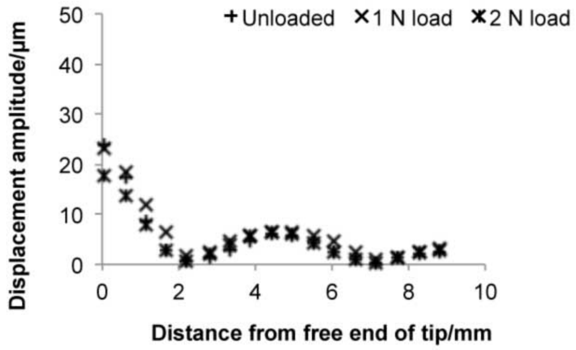
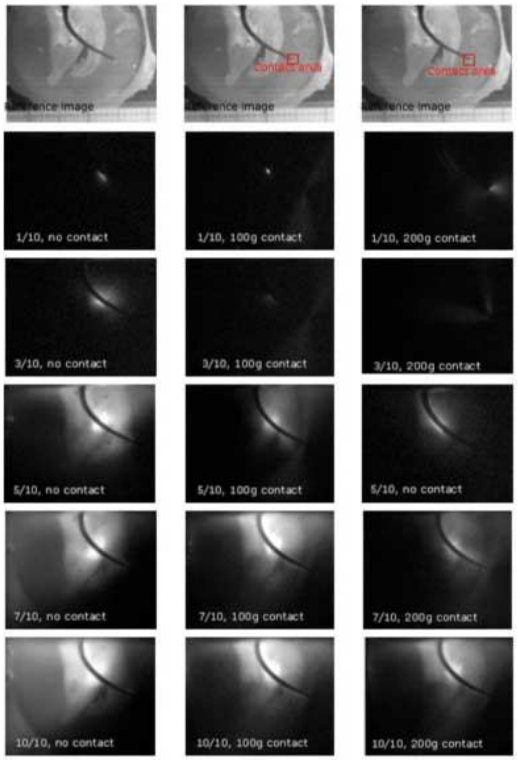
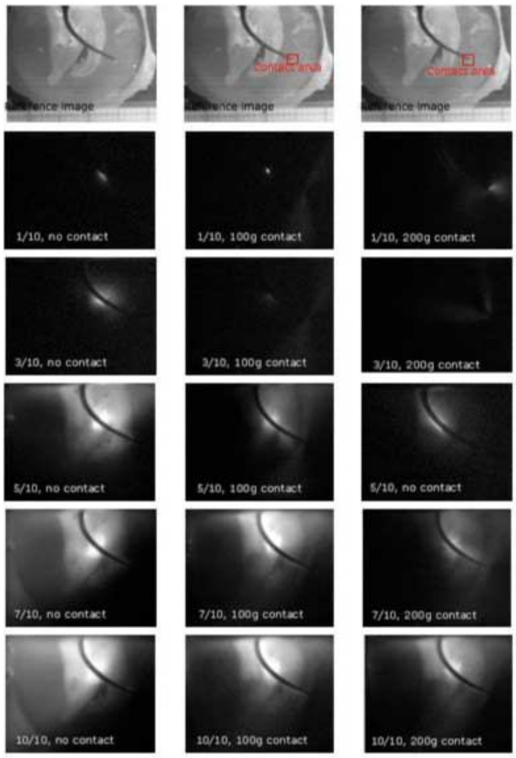


Figure 3 Chemiluminescence emission during operation of the A probe (a) and P probe (b) at different power settings and loadings. Illuminated regions indicate the presence of cavitation

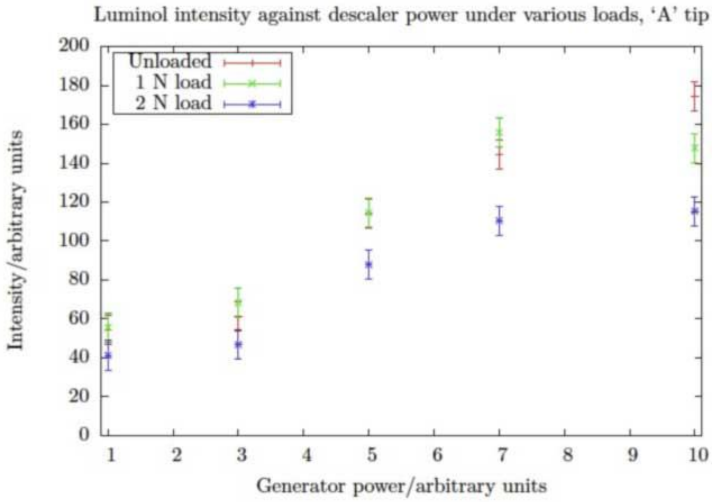


(a)

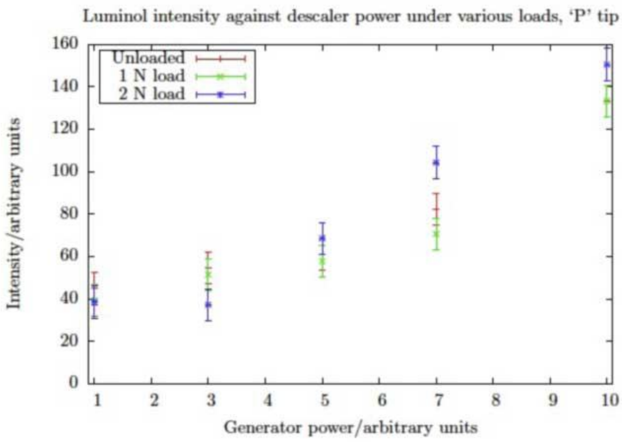


(b)

Figure 4 Luminol mapping under various loads side view using A probe (a) and P probe (b)



(a)



(b)