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Cavitation occurrence around ultrasonic dental scalers†

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Abstract

Ultrasonic scalers are used in dentistry to remove calculus and other contaminants from teeth. One mechanism which may assist in the cleaning is cavitation generated in cooling water around the scaler. The vibratory motion of three designs of scaler tip in a water bath has been characterised by laser vibrometry, and compared with the spatial distribution of cavitation around the scaler tips observed using sonochemiluminescence from a luminol solution. The type of cavitation was confirmed by acoustic emission analysed by a 'Cavimeter' supplied by NPL. A node/antinode vibration pattern was observed, with the maximum displacement of each type of tip occurring at the free end. High levels of cavitation activity occurred in areas surrounding the vibration antinodes, although minimal levels were observed at the free end of the tip. There was also good correlation between vibration amplitude and sonochemiluminescence at other points along the scaler tip. 'Cavimeter' analysis correlated well with luminol observations, suggesting the presence of primarily transient cavitation.

Key words: sonochemiluminescence, scanning laser vibrometry, dental instruments, cavitation

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1 Introduction

Ultrasonic scalers are used in dentistry to remove both subgingival (below gumline) and supragingival (above gumline) deposits from teeth. Compared with traditional hand instrumentation techniques, ultrasonic scalers have the primary advantage of significantly reduced treatment duration [1,2]. The design of scalers varies between manufacturers, but as shown in Fig. 1 is generally a J-shaped metal (often titanium) tip, approximately 25 mm in length, attached to a handpiece that is manipulated by the clinician. During use, a transducer in the handpiece induces vibration at ultrasonic frequencies in the tip, and the side of the free end of the tip is placed against the tooth, mechanically removing deposits on the surface. Frictional heating of the tooth is reduced by passing an irrigant solution through a small outlet on the underside of the tip [3]. It has been suggested that cavitation might occur in the cooling water as it flows over the tip and that this might aid the cleaning process [4].

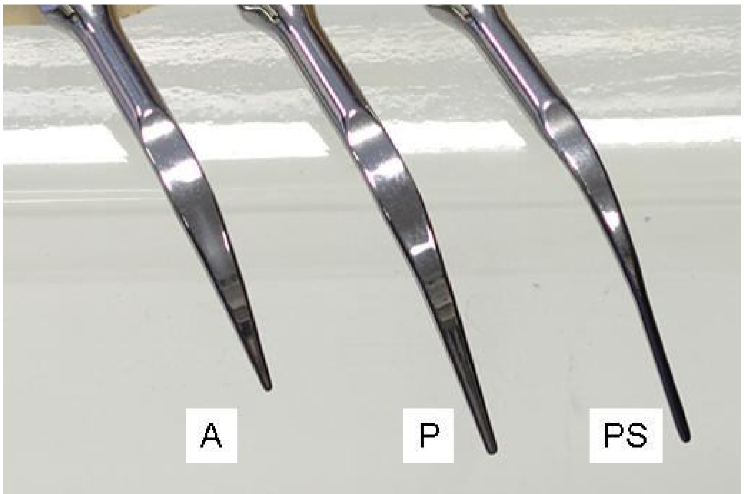

Fig. 1 A, P and PS tips, from left to right. The free end of the tip is placed side-on to the tooth during treatment. The threaded end of the tip is attached to the handpiece, containing an ultrasonic transducer.

Inertial cavitation occurs in liquids when the acoustic pressure during rarefaction becomes more negative than the saturated vapour pressure of the liquid, leading to rupture of the liquid and formation of cavities[5]. A sufficient negative pressure, in pure water of the order of 100 – 120 MPa, can be induced by ultrasonic scalers, such that cavitation will occur in liquid surrounding the tip[6]. Collapse of these cavities results in localised extreme conditions of pressure and temperature, up to 5000 K and 500 bar, which can in turn lead to pyrolysis of species which can volatilise into the bubble from solution [7]. Sonolysis products of water, specifically hydroxyl radicals and oxygen atoms, are highly oxidising species, as are secondary products such as hydrogen peroxide. Irrigant solutions often contain hydrogen peroxide to enhance the cleaning process. The physical effects of cavity collapse are also thought to aid surface cleaning, *via* the formation of microjets that impact on a surface when collapse occurs within close proximity[8].

In order to assess the role that cavitation plays in deposit removal from teeth, it is first necessary to identify the distribution of cavitation around each tip, so that possible differences due to variations in tip design can be elucidated. No data on cavitation distribution around ultrasonic scaler tips exists in the literature. Our hypothesis was that regions of high cavitation activity would be associated with the tip regions that have the greatest displacement during scaler operation.

Scanning laser vibrometry, SLV, has successfully been used to analyse the vibrational motion of ultrasonic scaler tips[9, 10]. Briefly, the technique works by measuring 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. There exists a wide variety of methods for measuring cavitation activity[11-13]. Luminol photography was employed for this work[14], since it gives spatially-resolved information on the occurrence of cavitation. Luminol sonochemiluminescence occurs through reaction with pyrolysis products of cavitation in aqueous systems. A long-exposure photograph can be used to assess regions of cavitation activity in a solution. A 'Cavimeter'[13], recently developed by the National Physical Laboratory, NPL, was used to analyse the acoustic output from a scaler tip in solution. A measure of the intensity of the driving frequency and the cavitation activity were obtained in order to correlate with luminescence measurements.

A full analysis of the role that cavitation might play needs the determination of scaler behaviour under a wide range of conditions. As a first step, we relate in this work the cavitation output from three different styles of dental tips, measured with a 'Cavimeter' from NPL, and observed *via* luminol photography, with the vibration characteristics measured by SLV in order to determine the spatial distribution of cavitation.

2 Experimental

All reagents were analytical grade and obtained from Sigma-Aldrich Co., UK, unless otherwise stated, and were used as received. The ultrasonic scaler was a Piezon miniMaster provided by Electro Medical Systems, Nyon, Switzerland, and was supplied with A, P and PS tips, as shown in Fig. 1. The scaler operates at a nominal frequency of 30 kHz, and can be set to any of ten incremental power settings from a control panel. For this work, power settings of 1/10, 5/10 and 10/10 were used.

2.1 Assessment of tip vibration characteristics

The vibrational motion of each tip was characterised by SLV as described by Lea *et al.*[10]. A tip was clamped into position so that it was fully-immersed in a water bath. Care was taken to ensure that the position was reproducible between different experiments. 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. The motion in the plane of the tip was measured; any lateral motion is not reported here. It has been measured and is significantly smaller than the longitudinal vibration, which is commonly used as a measure of the performance or output of the scaler tip. 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, as in Fig. 2. Variations in the length and curvature of each tip led to differences in the distance between scan points such that the inter-point distance was 0.54 mm for the A tip, 0.44 mm for the P tip and 0.55 mm for the PS tip, and the number of scan points was 15 for the A tip, 23 for the P tip and 19 for the PS tip. 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 power setting.

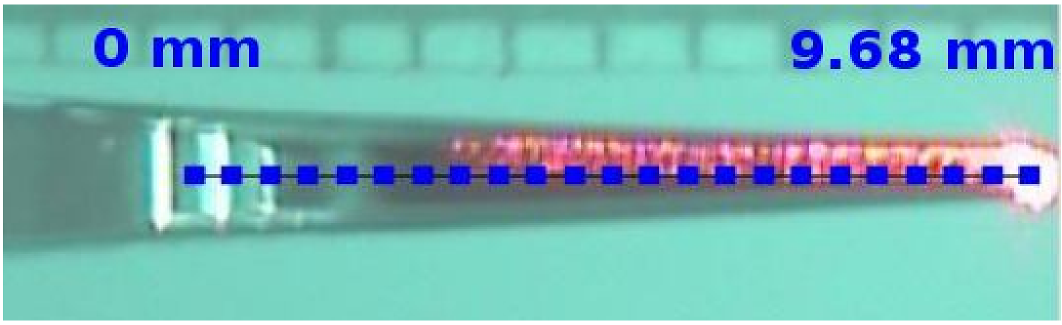

Fig. 2 Example of scan points layout for laser vibrometry, in this case along the P tip.

2.2 Luminol photography

Observation of cavitation activity was from the luminescence of 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[14].

A scaler tip was immersed in 50 cm^{3} of luminol solution in a flat-sided glass container, and clamped into position in sight of a Canon EOS 30D digital camera, set to ISO 3200 sensitivity. The

Cavimeter sensor and the tip handpiece were clamped onto the same stand and kept in the same position for each experiment. A Canon EF 100 mm f/2.8 USM Macro lens was used for imaging at the close-focus distance, corresponding to 1:1 reproduction. The apparatus was sealed in a light-proof box, and light emission recorded for 30 seconds of scaler operation. The procedure was repeated for each tip design, at low, medium and high power settings, with freshly-made luminol solution used 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[15].

2.3 'Cavimeter'

The ‘Cavimeter’ was developed by NPL[16] to provide a quantitative estimate of cavitation activity in a wide variety of circumstances. It consists of a strip of piezoelectric material embedded in a sound absorbing plastic cylinder. The design of the sensor is such that the response arises solely from activity inside this cylinder. The signal produced is integrated over a 2 s period and analysed in three ways; the ‘direct field’ value correlates the response at the fundamental driving frequency (in this case ~ 30 kHz) arising from the source as well as linearly oscillating bubbles. The ‘subharmonic’ measurement is recorded at frequencies of one-half and one-quarter of the fundamental and are indicative of the onset of transient cavitation. This type of cavitation is also quantified by measuring the ‘cavitation’ signal from emission at high frequencies between 1.5 and 5 MHz which arise from shock waves emitted by the collapse of transient bubbles[17, 18] although stable cavitation can also give signals in this region.

The scaler tip under investigation was surrounded by the cylindrical ‘Cavimeter’ sensor, placed into a glass beaker and immersed in 50 cm^3 of freshly-drawn deionised but not degassed water. The ‘Cavimeter’ monitor was attached to the sensor, and the zero levels set. Care was taken to ensure that the scaler tip was completely immersed in water and positioned in the same place relative to the cavimeter for each experiement. *The handpiece was aligned parallel to the cylindrical axis of the sensor and inserted so that the top and bottom of the exposed tip were equidistant from the top and bottom of the sensor.* The ultrasonic scaler was switched on for approximately 10 seconds, until the ‘Cavimeter’ readings were stable. An average of three successive measurements of the ‘direct field’ and ‘cavitation’ (i.e high frequency output) measurements were recorded while changing the power. No hysteresis effects were noted on increasing and decreasing the power. The procedure was repeated for each tip design, at all power settings and with freshly drawn water in each case.

3 Results and discussion

3.1 Vibration characteristics of ultrasonic scaler tips

The measured maximum displacement amplitudes of the ultrasonic scaler tips are shown in Fig. 3. Only the magnitude of the displacement is presented, the sign is omitted for clarity. The direction of motion of the end of the tip is opposite that of the middle section. The exaggerated displacement of a P tip at extremes of displacement can be seen in the computer reconstruction of the SLV data in Fig. 4. The vibrational antinode with the greatest displacement amplitude was found to always occur at the free end of each tip. Maximum displacement amplitudes at power 10/10 were measured to be 35.7±6.3 μm for the A tip, 21.9±3.9 μm for the P tip and 28.6±7.4 μm for the PS tip. A further antinode was found to occur for each tip, 7.6 mm, 8.9 mm and 6.1 mm from the free end for A, P and PS tips respectively.

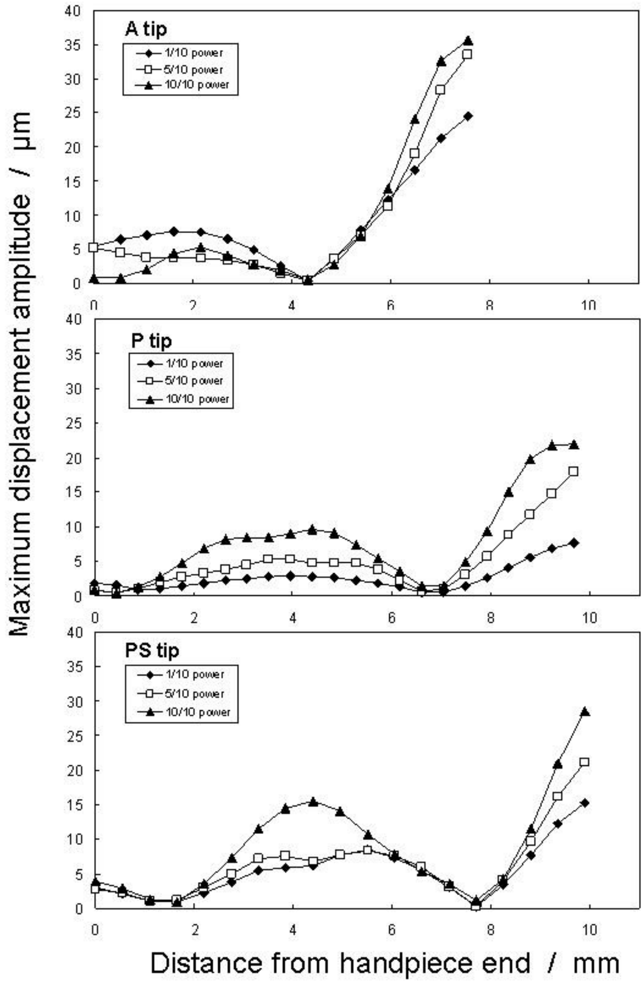

Fig. 3 Maximum displacement amplitude for each scan point of each tip. (a) A tip, (b) P tip, (c) PS tip. The origin on the displacement axis corresponds to the ‘angle’ of the scaler tip; the largest distance corresponds to the free end.

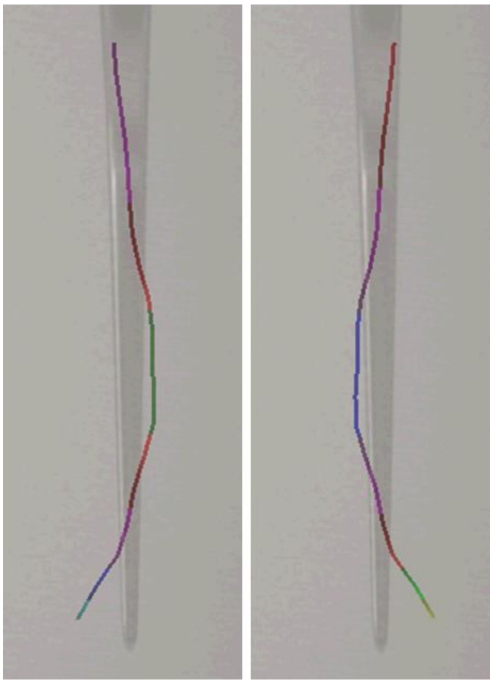

Fig. 4 Computer generated, exaggerated images of a P tip at maximum displacement

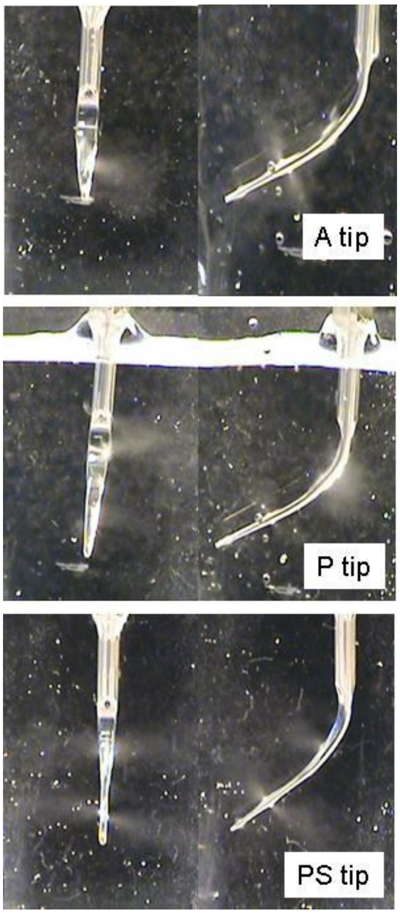

Fig. 5 Photographs of scaler tips in operation at power 10/10. (a) A tip, (b) P tip, (c) PS tip.

To confirm that these are cavitation bubbles, emission from luminol was recorded under the same conditions and the results are shown in Fig. 6. Although all power settings were used, only photographs from the highest power setting experiments are shown. Data from other experiments are presented in Table 1. The data shows intense regions of activity surrounding the bend for each tip, while little to no activity was observed at the free end of the tip. The intensity of all pixels in each image was summed and the results are presented in Table 1. As expected, higher power settings produced the greatest intensity, and therefore the greatest amount of cavitation, for each tip. Comparison of Figs. 4 and 5 shows that the spatial distribution of luminol emission is similar to the bubble clouds observed during scaler operation.

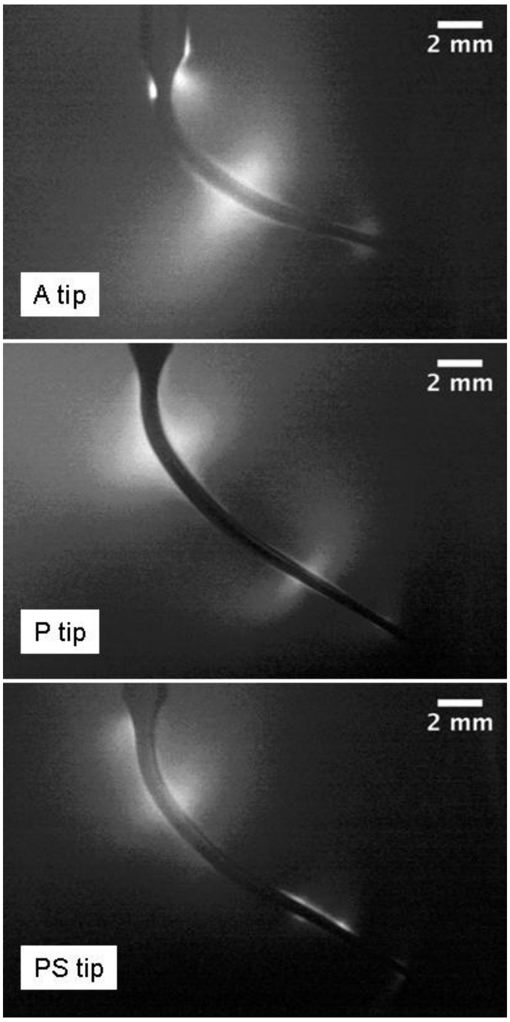

Fig. 6 Luminol photography of A, P and PS tips at power 10/10. Light regions indicate areas of high cavitation activity, with dark regions indicating little or no activity.

Table 1. Relative intensity of luminol emission

Relative intensity of luminol emission			
Tip	Power 1/10	Power 5/10	Power 10/10
A	3.31	8.64	11.54
P	1.00	2.05	12.85
PS	1.00	1.15	5.92

3.3 'Cavimeter' analysis

Monitoring luminol emission cannot differentiate between 'stable' and 'transient' (or inertial) cavitation. The latter would be expected to be dominant in the type of sound field produced by a scaler. There was a good correlation between the 'direct field' measurements from the 'Cavimeter' and the luminol emission showing that higher power settings produced larger amounts of cavitation. 'Cavimeter' readings also produced some evidence of sub-harmonic signals although there was considerable variation in the values obtained. More convincing evidence of the presence of transient cavitation is presented in Fig. 7 which shows a comparison of 'Cavimeter' measurements of transient cavitation (i.e. high frequency broadband signals) and luminol emission measurements for the three tips. The absolute measurements have been scaled relative to the maximum signal.
While the agreement is not perfect, both measurements show the same trend in increase, strongly suggesting that the acoustic emission and luminol chemiluminescence have the same origin, i.e. transient cavitation bubbles generated around the vibrating scaler. The agreement for the PS tips is less satisfactory although it should be noted that this is not unexpected since the absolute values of both luminol and acoustic emissions were by far the lowest for this tip and the variation in signals much smaller.

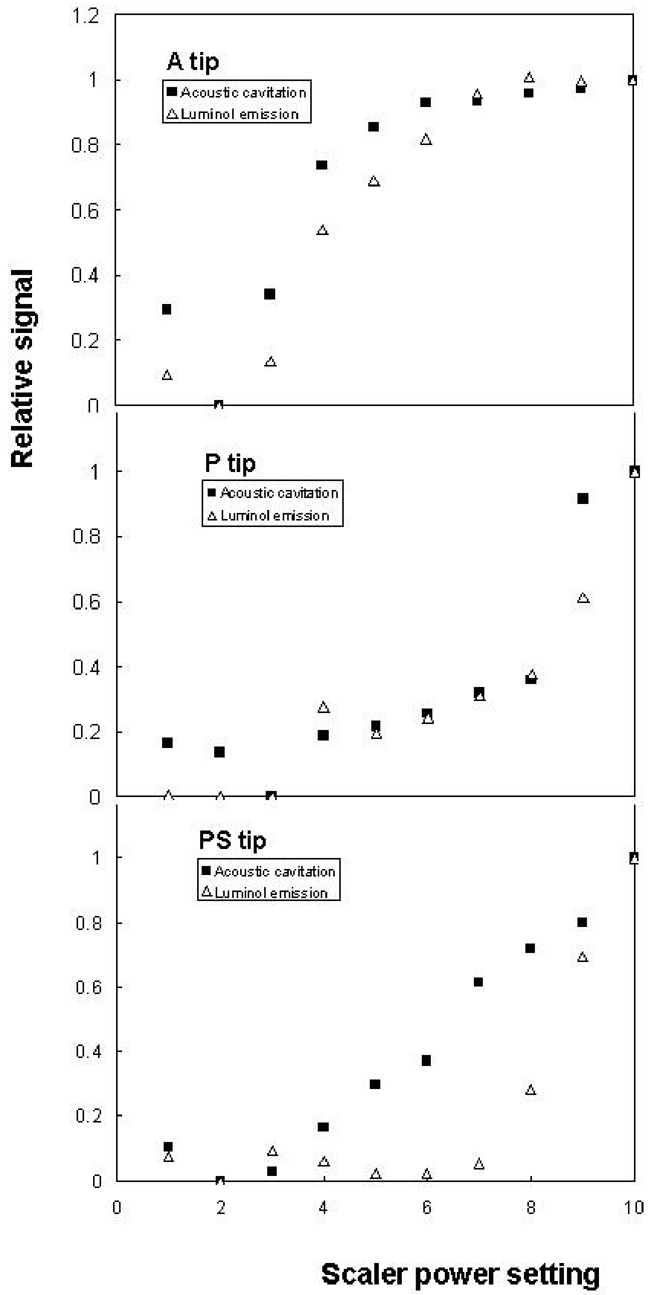

Fig. 7 A comparison of the results obtained via the 'Cavimeter' device and by luminol photography.

3.4 Further Discussion

It has been suggested that cavitation can be generated in the irrigant solution that is pumped over the surface of the tip[19]. This work has shown that use of higher generator power settings increases cavitation activity over that of low power settings, in line with previous observations [6], and with both luminol and 'Cavimeter' techniques. However, the amount of cavitation produced depended on the tip employed. Higher levels of cavitation activity were observed around the A and P tips, with only half as much observed around the PS tip. The almost-cylindrical cross section of the PS tip may be a factor in this difference. A cylinder is a remarkably ineffective shape for displacement of water (and hence generation of negative pressures), whereas a thin, rectangular cross section is significantly more effective. As a simple analogy, compare the paddle of an oar to the shaft and the difference in effect is plain. Therefore, the wider cross sections of the A and P tips would be expected to displace larger volumes of water than the cylindrical PS tip, leading to the observed difference in cavitation activity between the tips. The highest levels of cavitation activity were observed around vibration antinodes close to the bend in each tip. Surprisingly, while the displacement amplitude was greatest at the free end of the tip, little to no cavitation was observed at the free end using luminol photography.

A similar explanation may apply here. Each tip tapers towards the free end to a narrow end. Thus, even though the end shows large motion, its shape may mean that water flows easily around it so that the large negative pressures required for cavitation are not generated in its wake.
In typical clinical use, the tip of the scaler is contacted against a tooth and so applies a load at the free end of the tip orthogonal to the direction of vibration. Further work is underway to ascertain the effects of clinically-relevant loading of the scaler. While the work reported here concerns unloaded tips, it is relevant where scalers may be operated in pools of irrigant or liquid between teeth and gums. It is also possible that physical effects, such as streaming, may be more relevant to cleaning efficiency than cavitation activity and measurements of these factors will be reported in due course. With the current drive towards slimmer scaler tips [20], an understanding of how the shape and design affects the generation of cavitation is important and the results reported here provide a base for comparison of measurements under other conditions.

4 Conclusion

A good correlation has been found between vibrational antinodes occurring during operation of ultrasonic scalers with cavitation activity around the scaler tip. Significant differences in the amount of cavitation generated have been found between different tip designs which tentatively suggests an influence of tip profile on the resultant cavitation. Despite showing the largest motion, little cavitation was detected at the free end of the tips and this again may be due to the shape of the tip at its end. Good agreement was found between optical, acoustic emission and luminol emission methods for detecting and measuring cavitation.

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